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Assessment of Pacific Cod (*Gadus macrocephalus*) for Hecate Strait (5CD) and Queen Charlotte Sound (5AB) in 2013

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

The status of populations of Pacific Cod (*Gadus macrocephalus*) in Hecate Strait (Area 5CD) and Queen Charlotte Sound (Area 5AB) in British Columbia were assessed using Bayesian delay difference models. Despite large uncertainty, biomass in Hecate Strait is estimated to have been on a gradual increasing trajectory since 2001, but is below the median accepted Upper Stock Reference point for Area 5CD. Recruitment is estimated to have been below average for the past two decades. In Queen Charlotte Sound, biomass and recruitment are estimated to have been below the historical average since the mid-1990s. Model estimates of biomass and stock status in both management areas were very sensitive to prior assumptions about natural mortality, variance in the mean weight data, and the goodness of fit to the indices of abundance, particularly the commercial CPUE data. Harvest advice was produced in the form of decision tables that summarized the probability of breaching biomass-based and fishing-mortality based reference points for Area 5CD, and the probability of breaching fishing-mortality based reference points for Area 5AB, for a range of fixed 2014 catch levels. Due to model sensitivity to a number of assumptions, decision tables were provided using: (i) a Base Case model configuration; and (ii) a model-averaging approach intended to integrate uncertainty among alternative model configurations. Uncertainty in estimates of productivity parameters implied large uncertainty in MSY-based reference points, and their use is not recommended for decision-making in this assessment cycle. Instead, reference points based on historical reconstruction of long-term average biomass and fishing mortality were accepted as alternatives for Area 5CD. The use of historical biomass-based reference points was proposed for Area 5AB. However, their adoption was rejected for use in this area, due to uncertainties in the estimated historical biomass time series. Two CSAP review meetings were held for this assessment. The first, in January 2014, accepted the advice for Area 5CD and recommended revision of the Area 5AB assessment due to an error in the annual mean weight data. A second meeting was held in December 2014, where the advice for Area 5AB was accepted.

Évaluation de la morue du Pacifique (*Gadus macrocephalus*) dans le détroit d'Hécate (5CD) et le détroit de la Reine-Charlotte (5AB) en 2013

RESUME

L'état des populations de morue du Pacifique (*Gadus macrocephalus*) dans le détroit d'Hécate (zone 5CD) et le détroit de la Reine-Charlotte (zone 5AB) en Colombie-Britannique a été évalué à l'aide de modèles bayésiens de type différence-délai. Malgré une grande incertitude, on estime que la biomasse dans le détroit d'Hécate connaît une hausse graduelle depuis 2001, mais se situe en dessous du point de référence supérieur du stock médian accepté pour la zone 5CD. On estime également que le recrutement est inférieur à la moyenne depuis les deux dernières décennies. Dans le détroit de la Reine-Charlotte, on estime que la biomasse et le recrutement se trouvent sous la moyenne historique depuis le milieu des années 1990. Les estimations modélisées de la biomasse et de l'état du stock dans les deux zones de gestion étaient très sensibles aux hypothèses antérieures sur la mortalité naturelle, les écarts dans les données sur le poids moyen et la validité de l'ajustement aux indices d'abondance, particulièrement les données sur les prises commerciales par unité d'effort. Des avis sur les prélèvements ont été produits sous la forme de tables de décision qui résument la probabilité de dépassement des points de référence fondés sur la biomasse et la mortalité par pêche dans la zone 5CD, et la probabilité de dépassement des points de référence fondés sur la mortalité par pêche dans la zone 5AB, en fonction d'une fourchette de niveaux de prises fixes en 2014. En raison de la sensibilité du modèle à un certain nombre d'hypothèses, les tables de décision utilisent une configuration du modèle de référence et une méthode de combinaison de modèles conçue pour intégrer les incertitudes entre autres configurations du modèle. L'incertitude des estimations des paramètres de productivité laisse entendre une grande incertitude à l'égard des points de référence fondés sur le RMS, et il n'est pas recommandé de les utiliser pour prendre des décisions dans le cadre du présent cycle d'évaluation. Les points de référence fondés sur la reconstitution historique de la biomasse et sur la mortalité par pêche moyenne à long terme ont plutôt été reconnus comme des solutions de rechange pour la zone 5CD. Il a été proposé d'utiliser les points de référence fondés sur la biomasse historique dans la zone 5AB. Cette proposition a toutefois été refusée en raison des incertitudes liées à l'estimation de la série chronologique de la biomasse historique. Cette évaluation a fait l'objet de deux réunions d'examen du Centre des avis scientifiques du Pacifique. À la première réunion, en janvier 2014, on a accepté l'avis formulé pour la zone 5CD et la révision recommandée de l'évaluation de la zone 5AB en raison d'une erreur dans les données sur le poids moyen annuel. À la deuxième réunion, tenue en décembre 2014, l'avis concernant la zone 5AB a été accepté.

INTRODUCTION

Two CSAP review meetings were held for this assessment. The first, on January 9-10, 2014, accepted the advice for Area 5CD and recommended revision of the Area 5AB assessment due to an error in the query used to extract data for calculating annual mean weights. A second meeting was held on December 8, 2014, where the advice for Area 5AB was accepted, with some modifications. These two meetings are referred to occasionally throughout this document, as they resulted in some differences in reference points and mean weight calculations for the two areas.

STOCK STRUCTURE AND LIFE HISTORY

Pacific Cod (*Gadus macrocephalus*) is a relatively short-lived, fast-growing member of the family Gadidae. Other common names in British Columbia (BC) include grey cod (or gray cod). Populations of Pacific Cod are distributed from California, throughout the waters of BC, Gulf of Alaska and the Bering Sea to Russia, Korea, Japan and China (Hart 1973). Maximum observed age in British Columbia is around 10-11 years (Westrheim 1996; this document), while a maximum age of approximately 13 years has been reported for Alaskan stocks (Roberson 2001). Maximum length recorded in British Columbia is 100 cm (Hart 1973), although some larger specimens have been observed in Alaska and Russia (Westrheim 1996). Pacific Cod are demersal spawners, with several studies reporting that spawning most likely occurs during February to March. A comprehensive review of the biology, life history and distribution of Pacific Cod in British Columbia is provided by Westrheim (1996).

Four stocks of Pacific Cod are defined for management purposes on the BC coast: Strait of Georgia (4B); West Coast Vancouver Island (3CD); Queen Charlotte Sound (5AB); and Hecate Strait (5CD). This study focuses on the populations in Queen Charlotte Sound and Hecate Strait (Figure 1).

Recent genetic analyses have identified a distinction between North American and Asian Pacific Cod populations, and have shown some evidence for distinction between Alaskan populations and those south of Dixon Entrance in British Columbia (reviewed in Appendix E). There is also evidence that fish taken off the coast of Washington and the west coast of Vancouver Island may be distinct from fish sampled within the Strait of Georgia or Puget Sound. However, linkages, if any, among stocks in BC and those in Alaska remain poorly understood. To date it is uncertain whether genetic population structure exists within BC waters (Appendix E).

Population dynamics of Pacific Cod in BC have been characterized by large variations in abundance, based on reconstructions driven by fishery catch rates, most likely as a function of large recruitment events followed by large opportunistic fishery catches. However, other hypotheses, including predator-prey cycles, density-dependent growth and mortality,and northward water transport have also been proposed (reviewed by Westrheim 1996). Natural mortality has been estimated as high as 0.6 - 0.65 y^{-1} in some stock assessments (e.g., Fournier 1983; Sinclair and Starr 2005) although lower estimates (~0.4 y^{-1}) have also been obtained (Sinclair et al. 2001). The combination of apparently volatile dynamics with short life span and high natural mortality suggests periods of over/under harvest could result if harvest strategies are not designed to be robust to these features. However, in the context of the BC integrated groundfish fishery, constraints imposed by quotas for other species mean that single-species considerations alone do not always dictate the best harvest strategy.

ECOSYSTEM CONSIDERATIONS

Prey and predators

Pacific Cod are omnivores, eating a diet of mainly marine invertebrates, including amphipods, euphausiids, shrimp and crabs. At around 50-55 cm they also become piscivorous, with Pacific Sand Lance (*Ammodytes hexapterus*) and Pacific Herring (*Clupea harengus pallasi*) becoming important components of the diet (Westrheim 1996). Juvenile Sablefish (*Anoplopoma fimbria*) and adult Pacific Hake (*Merluccius productus*) have also been reported in the diet of Pacific Cod off the west coast of Vancouver Island (Ware and McFarlane 1986). Pacific Cod have been reported in the diets of Pacific Halibut (*Hippoglossus stenolepis*), North Pacific Spiny Dogfish (*Squalus suckleyi*), sea birds, seals and sealions (Westrheim 1996).

Walters et al. (1986) demonstrated a Pacific Cod-Herring predator-prey interaction in Hecate Strait, in contrast to Ware and McFarlane (1986). Simulation models were developed by Walters et al. (1986) to explicitly model the effects of Pacific Cod predation on Pacific Herring. The simulations were able to mimic recruitment trends in both species. Walters et al. (1986) concluded that availability of Pacific Herring prey could be an important driver of Pacific Cod production in Hecate Strait, and, similarly, that Pacific Cod predation could be a significant driver of Pacific Herring abundance. These authors acknowledged that there are alternative hypotheses for cycles in abundance of Pacific Cod and Pacific Herring (e.g., environmental forcing; see below) and suggested that large-scale management experiments may be the only way to distinguish among competing hypotheses.

Environment

A large number of studies have investigated linkages between recruitment and environmental indices for Pacific Cod in Hecate Strait. The dominant hypothesis is an inverse relationship between recruitment and northward water transport (i.e., northward advection of larvae) (Tyler and Westrheim 1986; Tyler and Crawford 1991). Northward water transport has been shown to be positively correlated with mean annual sea level at Prince Rupert during the spawning season, which in turn has been used as an explanatory variable for recruitment by a number of authors (Fournier 1983; Sinclair et al. 2001; Sinclair and Crawford 2005; Sinclair and Starr 2005). Westrheim (1996) provides a review of the major alternative studies.

Other species

Other species caught with Pacific Cod include Arrowtooth Flounder (*Atheresthes stomias*), Yellowtail Rockfish (*Sebastes flavidus*), Pacific Ocean Perch (*S. alutus*), Lingcod (*Ophiodon elongatus*), Silvergray Rockfish (*S. brevispinis*), English Sole (*Parophrys vetulus*) and Big Skate (*Raja binoculata*) (Figure 2). Vessels catching Pacific Cod must hold quota for all quota species encountered. Since 1996, there has been 100% at-sea observer coverage on commercial bottom trawl vessels in BC. At-sea releases are recorded by observers and counted against the vessel's quota, according to agreed-upon discard mortality rates published in the integrated fishery management plan (DFO 2015).

FISHERIES

Pacific Cod in British Columbia are caught almost entirely in the groundfish bottom trawl fishery, which is part of BC's integrated groundfish fishery. Pacific Cod is one of the principal target species of the trawl fishery in Hecate Strait. Currently, the majority of the BC Pacific Cod catch is taken from in Hecate Strait (Area 5CD) (Figure 3).

Pacific Cod are distributed throughout Area 5CD at depths mainly less than 150 m. Pacific Cod density, measured by commercial catch per unit effort (see Appendix B), appears to be highest over the Two Peaks/Butterworth, White Rocks, Shell Ground, Reef Island, and Horseshoe fishing grounds (Figure 1). In Queen Charlotte Sound (Area 5AB), Pacific Cod are caught mainly around the edge of Goose Island Bank in Area 5B and on Cape Scott and Mexicana Banks, north of Vancouver Island, in Area 5A (Figure 1). The depth range of capture is approximately 60 – 160 m. Annual reported catches of Pacific Cod in both Hecate Strait and Queen Charlotte Sound have shown considerable variability since the beginning of the time series in 1956 (Figure 3, Tables 1 and 2).

In Hecate Strait (Figure 3a), major peaks in catches (landings plus estimated discards) occurred in 1958 (5,702 t), 1965 and 1966 (8,870 t and 9,156 t), 1979 (5,736 t), 1987 (9,542 t), and 1991 (7,747 t). These peak years may be contrasted with years of low catches in 1961 (1,528 t), 1970 and 1971 (1,188 t and 1,333 t), 1985 (1,053 t), and the minimum on record in 2001 (214 t). Reported catches have increased since 2001 to 701 t in 2012, although it should be noted that recent low catches are partially a result of lowered quotas in the early to mid-2000s. Catch was reported by USA vessels from 1956 to 1978. The estimated USA portion of the total catch was approximately 15% over these years (Table 1).

Catches in Queen Charlotte Sound (Figure 3b) also showed significant variability over the time series. Major peaks in catches occurred in1957 (2,625 t), 1965 (1,983 t), 1972 and 1975 (2,415 t and 2,470 t), 1987 (3,209 t), and 1991 (2,206 t). Low catch years included 1961 (259 t), 1970 (278 t), 1983 (184 t), 2000 (67 t) and the lowest year on record 2008 (35 t). Significant catches were reported by USA vessels from 1956 to 1980. The estimated USA portion of the total catch was approximately 50% over these years (Table 2).

Prior to the introduction of at-sea observer coverage in 1996, estimates of at-sea releases (discards) for the period 1956-1995 were obtained from fishing logbooks (Figure 4). These estimates are considered an underestimate of the actual releases. Estimates in years following the introduction of 100% at-sea observer coverage in 1996 can be considered to be more accurate. Since 1996, the proportions of estimated discards have been considerably higher than in years before at-sea observers (Figure 4), especially in Queen Charlotte Sound, largely as a result of reduced total catches. Pacific Cod can be legally discarded by trawlers in BC. However, on-board observers first estimate the quantity being discarded and it is assigned a discard mortality rate which is counted against the vessel's Pacific Cod quota. Therefore, in addition to greater accuracy in reporting of discards since 1996, incentives to avoid discarding have also been greater.

Japanese and Soviet vessels also trawled in waters off BC in the late 1960s and early 1970s. These vessels were mainly targeting rockfish and likely at depths greater than 150 m. The bycatch of Pacific Cod in these fisheries is, however, unknown. Given uncertainty in foreign catches and discards in the earlier parts of the time series, total catch estimates should be considered underestimates prior to 1996.

Bottom trawl fishing effort has been somewhat cyclic in both areas, especially in Hecate Strait (Figure 5). Total effort of all trawl vessels has declined in both areas since peaking in 1993 (Hecate Strait) and 1995 (Queen Charlotte Sound). A detailed analysis of catch per unit effort (CPUE) is provided in Appendix B. As noted by Sinclair (2000), however, there are a number of problems with the use of commercial catch per unit effort data as an index of biomass for Pacific Cod. It has been suggested that changes in the management regime from an unrestricted fishery prior to 1992, to the introduction of TACs (1992-1996) and then to Individual Vessel Quotas (IVQs) (1997-present), as well as several increases in mesh size, have affected the underlying relationship between commercial CPUE and abundance, and the relationship between fishing effort and fishing mortality. In recent years of lower Pacific Cod quotas, many fishing masters report actively avoiding Pacific Cod to prevent their Pacific Cod quota being exceeded before catching available quotas for other species. Fournier (1983) noted similar problems with relating fishing effort to fishing mortality for this fishery. Sinclair et al. (2001) analyzed the spatial distribution of fishing effort in Hecate Strait and reported that there had been little fishing over Butterworth, White Rock, Bonilla and Horseshoe grounds (Figure 1), which had previously been locations with the highest CPUE. They also cited industry reports that key Pacific Cod fishing grounds had been avoided to preserve Pacific Cod quota for bycatch in other fisheries (Sinclair et al. 2001). We do not provide a detailed analysis of spatial fishing effort in this document but recommend it as an avenue of future research to improve understanding of the CPUE data and drivers of fishing effort (e.g., Branch and Hilborn 2008).

MANAGEMENT HISTORY

The history of Pacific Cod management from 1984 to 2013 is summarized in Tables 3-6. The tables list total allowable catches (TACs), landings and carryovers, area closures and mesh restrictions.

Groundfish fisheries were managed by calendar year until 1996. Beginning in 1997-98 the fishing year changed to April 1 – March 31. In 2010 – 2011 the fishing year was changed again to February 21 to February 20. Throughout this document, fishing years are defined as beginning April 1 for all years, and are referenced by starting year, e.g., fishing year 1997 runs from April 1, 1997 to March 31, 1998.

Area 5AB: Queen Charlotte Sound

Annual TACs were introduced for Pacific Cod in Queen Charlotte Sound in fishing year 1997 (Table 3). Before 2005, there was no scientific advice for this area and the TAC was initially established at 260 t, which was the low end of the range of observed catches (Sinclair and Starr 2005). The TAC remained unchanged until 2004 when it was increased to 390 t based on advice from the fishing industry to Fisheries Management that Pacific Cod abundance had increased. There were also carryover amounts in the 1999-2004 fishing years. Between 1997 and 2002, the fishery did not catch the TAC (plus carryover) in each year, with a low of 18% taken in 2000 and a high of 56% in 2002. The TAC plus carryover was exceeded by 16% in 2003. The TAC remained at 390 t from 2004 until 2010. In 2010 the quota was exceeded by 22% and in 2011 the TAC was increased to 590 t.

Other management measures have been used to control the Pacific Cod fishery in Area 5AB. Voluntary increases in mesh size for various portions of Queen Charlotte Sound were suggested in 2007 for vessels fishing shallower than 60 fm. This was then regulated in 2011 (Table 5).

Area 5CD: Hecate Strait

Annual TACs were introduced in the 5CDE area in 1992 (Sinclair and Starr 2005). Catches in Area 5E (West Coast Haida Gwaii) have been negligible and we do not further discuss this area. The original Area 5CD 1992 TAC was 3,400 t and landings that year exceeded this figure by 48% (Table 4). The TAC was increased to 5,100 t in 1993, and then reduced in steps to 1,000 t in 1998. The low catch in relation to the TAC in 1999 led to a carryover of 283 t in 2000. The TAC was reduced to 200 t in 2001 due to very low assessed stock biomass (Sinclair 2000) and no carryovers were allowed. The TAC was maintained at 200 t in 2002. The 2003 TAC was initially set at 200 t but results from the Hecate Strait Pacific Cod monitoring survey, commercial CPUE, and input from the trawl fleet indicated that Pacific Cod abundance had increased in the area. Consequently, the TAC was increased to 400 t in the winter of 2003 and the TAC was maintained at 400 t for 2004. The TAC was increased to 800 t in 2005 and remained at that level until 2009. In 2010 the TAC was increased to 1,200 t and has remained at that level until the present.

Other management measures have been used to control the Pacific Cod fishery in Area 5CD. Voluntary increases in mesh size for various portions of areas 5CD were suggested as early as 1989 for this fishery and were regulated in 1995 (Table 5). There have also been a number of closures instituted in Hecate Strait to protect spawning biomass (Table 6, Figure 6). The Horseshoe and Reef Island fishing grounds, as well as the shallow Dogfish Bank, were closed from January 1 – April 15 in 1991 and 1992. A slightly smaller area was closed for the same months between 1996 and 2001 (Table 6, Figure 6). The closed area was again increased in size in February 2001 to include all of Hecate Strait south of a line between the latitude of Rose Spit and north of a line just south of Reef Island (Figure 6). This closed all of the main cod fishing grounds except Two Peaks/Butterworth. Effective January 27, 2012 the size of the spawning closure was decreased, opening up the eastern side of Hecate Strait to fishing, including the White Rocks ground (Figure 6). Additionally, since 1996, there has been a closure from June 1-July 15 in the shallow portions of Area 5D for the protection of Dungeness crabs during the soft shell stage.

ASSESSMENT HISTORY

A number of methods have been used to assess Pacific Cod in Hecate Strait since the 1980s. Fournier (1983) developed an age-structured model and used it to test for evidence of age-dependent trends in natural mortality, density-dependent natural mortality and catchability, and also for evidence of an environmental factor affecting recruitment. Evidence was found for a relationship between mean sea level at Prince Rupert and recruitment, and also for density-dependent natural mortality. Natural mortality was estimated to be 0.65 y^{-1} by Fournier (1983). This author cautioned about the possibility of confounding among model parameters and systematic data biases that could influence conclusions from the analysis. Estimates of age were obtained from length-frequency analysis (Foucher and Fournier 1982).

Pacific Cod are one of the most difficult Pacific groundfish species to age. Annual rings (annuli) in otoliths, other bony structures and scales are difficult to distinguish from interannual growth checks (Beamish 1981; Chilton and Beamish 1982; Roberson 2001; Johnston and Anderl 2012). In British Columbia, age compositions have been estimated using length-based approaches, scales, otoliths and, currently, dorsal fin ray sections, although all methods present difficulties. In the absence of reliable direct age data, length-based approaches were used to assess the Hecate Strait stock during the 1990s (Haist and Fournier 1995[1]; 1996; 1997; 1998[2]). The last of these assessments (Haist and Fournier 1998) suggested that the stock had reached an historic low in 1996, followed by a slight rebound.

Sinclair (2000) used a simple surplus production model fit to a commercial CPUE index to assess the Hecate Strait stock in 2000. This author cited significant structural changes in the fishery during the 1990s resulting in changes in quality and comparability of fishery-dependent data available for the analysis. Changes included voluntary increases in mesh size in the commercial fishery and introduction of individual vessel quotas (IVQs) in 1997 as discussed above. Given the large structural differences between the previous length-based models and the surplus production model, Sinclair (2000) noted that results were remarkably comparable until 1994, with three estimated peaks in abundance occurring in 1965, 1974-5 and 1986-7. The two approaches diverged significantly after 1994, with the the length-based Multifan model estimating an increase in biomass while the surplus production model estimated a decline. The differences were interpreted to be due to differences in the indices of abundance used to tune the models, as well as structural model differences.

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[1] Haist, V. and Fournier, D. 1995. Hecate Strait Pacific Cod assessment for 1995 and recommended yield options for 1996. PSARC Working Paper G95-3.

[2] Haist, V. and Fournier, D. 1998. Hecate Strait Pacific Cod assessment for 1998 and recommended yield options for 1999. PSARC Working Paper G98-3.

Sinclair et al. (2001) developed a delay-difference model (Deriso 1980; Schnute 1985; Hilborn and Walters 1992) containing a Ricker stock-recruit function to assess Pacific Cod in Hecate Strait and off the west coast of Vancouver Island. Recruitment was assumed to be knife-edged at age 2 years. A report card summary of information available for the stock was also developed. The report card analysis from this assessment found biomass indicators to be in the "danger" and "low" categories with potential for increasing recruitment; and reported a general lack of information on other types of indicators for this species in BC. The delay difference model provided a better statistical fit to the data than the previously-applied surplus production model. However, biomass estimates followed a similar trend and magnitude (Figure 7). Retrospective analyses using only data up to 1995 tended to project large increases in biomass that were not predicted when the most recent CPUE data to 2000 were used. The authors noted that the model containing the most recent data predicted the stock to be less productive than the model containing only the earlier data.

The Hecate Strait Pacific Cod stock was last assessed in 2004 (Sinclair and Starr 2005) using a delay difference model with a Beverton-Holt stock-recruit function, based on the view that a Ricker type function with declining recruitment at high stock size was inappropriate for this species. As for the previous assessment, recruitment was assumed to be knife-edged at age 2 years. Model fits were presented with alternative combinations of fixing or estimating natural mortality (*M*) and the steepness parameter of the stock-recruit function, *h* (Mace and Doonan 1988). They reported similar fits and biomass estimates for the alternative scenarios but noted very different estimates of equilibrium MSY-based management parameters under alternative combinations of fixed and estimated steepness and *M*.

Estimates of biomass for the two preferred model runs were considerably higher than estimates from previous assessments (Figure 7). Given structural differences between these and previous models, and differences in the data to which the models were fitted, it is not appropriate to speculate on the source of the large difference in scale among models. However we note that the 2004 assessment was not directly fit to the commercial CPUE data as were previous assessments, but instead was fit to data from the Hecate Strait Assemblage Survey (Choromanski et al. 2005) and the Pacific Cod Monitoring Survey (Sinclair and Workman 2002). There were also differences in:

(i) weighting of the indices of abundance relative to the mean weight data, to which both sets of models were also fitted; and

(ii) the choice of other fixed variance parameters.

Key uncertainties of the analysis noted by Sinclair and Starr (2005) were:

(i) uncertainty in the growth function (model parameters and assumptions of stationarity); and

(ii) the possibility of violating the assumption of knife-edged recruitment at age 2 years, given evidence for younger fish in the length composition data from the commercial fishery.

Finally, an error was discovered in the model code used for this assessment several years after this assessment was published (see below).

Assessments using corrected code were repeated for English Sole (Starr 2009a) and Petrale Sole (Starr 2009b), but this was not done for Pacific Cod.

DATA SOURCES

DATABASES

Data were extracted from a number of different databases:

GFBio. *Biological samples and research cruise database.* Groundfish Section, Marine Ecosystems and Aquaculture Division, Science Branch, Fisheries and Oceans Canada, Pacific Biological Station. This data archive includes most of the groundfish specimen data collected since the 1950s. It therefore includes data from a variety of sources (port and at-sea commercial sampling, research survey sampling), collected using a variety of sampling methods.

GFCatch. *Canadian trawl landings, 1954-1995* (Rutherford 1999).

PacHarvTrawl. *Canadian trawl landings, 1996 to March 31, 2007.* SQL Server database, Groundfish Section, Marine Ecosystems and Aquaculture Division, Science Branch, Fisheries and Oceans Canada, Pacific Biological Station.

GFFOS. *Canadian trawl landings, April 1, 2007 to 2013.* View of the Fisheries and Oceans Canada (DFO) Fishery Operations (FOS) database. Groundfish Section, Marine Ecosystems and Aquaculture Division, Science Branch, Fisheries and Oceans Canada, Pacific Biological Station.

CATCH DATA

Commercial fishing data are presented in this document by fishing year which includes the period April through March, e.g., fishing year 1956 comprises the period April 1, 1956 to March 31, 1957. Landings data are presented separately for Canada and the USA (Tables 1 and 2). Combined USA-Canada landings data were obtained from the Pacific Marine Fisheries Commission reports for 1956-1981 and the USA landed portion was determined by subtracting the Canadian landed amount from the combined total for each year. In cases where the difference was negative, the USA landed amount was set to zero (Tables 1 and 2). Canadian data were obtained: from the GFCatch database for the period 1954-1995 (Rutherford 1999); from the PacHarvest database for the period 1996-March 31, 2007; and from the Fisheries and Oceans Canada (DFO) FOS database for the period April 1, 2007 until the present. The annual size composition of commercial catches and landings were estimated from port samples and at-sea samples collected by observers archived in the GFBio database. Survey descriptions

Hecate Strait Assemblage Survey

A series of multi-species groundfish bottom trawl surveys was conducted in Hecate Strait in May-June of 1984, 1987, 1989, 1991, 1993, 1995, 1996, 1998, 2000, 2002, and 2003 (Westrheim et al. 1984, Fargo et al. 1984, Fargo et al. 1988, Wilson et al. 1991, Hand et al. 1994, Workman et al. 1996, Workman et al. 1997, Choromanski et al. 2002a, Choromanski et al. 2002b). The results up to 2000 were reported in the 2001 assessment (Sinclair et al. 2001) and results from 2002 and 2003 were presented in the 2005 assessment (Sinclair and Starr 2005).

The original design of this survey assigned fishing locations by 10 fm depth intervals within a 10 nm grid of Hecate Strait. The survey was post-stratified for the purpose of calculating an abundance index for Pacific Cod (Sinclair 1999). The post stratification used 10 fm depth intervals for the entire survey area, thereby treating each depth interval as a single stratum.

The Hecate Strait Assemblage survey was designed as a systematic fixed-station survey. Despite attempts to apply post-sampling stratification, this approach had high survey variance (Sinclair et al. 2007). In 2004 the Hecate Strait Assemblage survey was discontinued in favour of the Hecate Strait Synoptic survey (described below).

Hecate Strait Pacific Cod Monitoring Survey

The TAC for Pacific Cod in Hecate Strait was reduced considerably for the 2001 fishing year because of a low assessed stock size. The assessment was based largely on abundance indices derived from commercial fishing catch per unit effort (CPUE). With the reduced TAC, fishers avoided areas of high Pacific Cod abundance in order to retain quota holdings for Pacific Cod while fishing for other species. This potentially biased the CPUE data relative to previous fishing practices and makes the assumption of a consistent relationship between CPUE and abundance through the early 2000s unlikely (Sinclair et al. 2001). While the Hecate Strait Assemblage Survey was conducted 11 times intermittently over a period of 22 years (between 1984 and 2005), the relatively low sample sizes in this survey coupled with the highly aggregated distribution of Pacific Cod in Hecate Strait resulted in high estimation variance and, therefore, reduced ability to track changes in abundance (Sinclair 1999). Recognizing this shortfall in the index, a survey optimized for Pacific Cod was implemented in Hecate Strait to monitor the population as it rebuilt. This survey was planned for a three-year period between 2002 and 2004 with fishing carried out in areas identified by experienced fishers as being good grounds for the species (Figure 1). A complete description of the survey design is presented by Sinclair and Workman (2002). The current stock assessment did not fit to this short index of abundance but it was used in bridging analyses (Appendix A).

Hecate Strait Synoptic Survey

The Hecate Strait synoptic groundfish bottom trawl survey is part of a coordinated set of long-term surveys that together cover the continental shelf and upper slope of most of the BC coast. The Hecate Strait synoptic survey has been conducted during May-June, in odd years since 2005. All the synoptic surveys follow a random depth stratified design. The survey area is divided into 2 km by 2 km blocks and each block is assigned to one of four depth strata based on the average bottom depth in the block. The four depth strata for the Hecate Strait survey are 10 – 70 m, 70 – 130 m, 130 – 220 m, and 220 – 500 m. Each year blocks are randomly selected within each depth strata.

The relative allocation of blocks amongst depth strata was determined by modeling the expected catches of groundfish and determining the target number of tows per stratum that would provide the most precise catch rate data for as many species as possible.

Queen Charlotte Sound Synoptic Survey

The Queen Charlotte Sound synoptic groundfish bottom trawl survey is part of a coordinated set of long-term surveys that together cover the continental shelf and upper slope of most of the BC coast. The Queen Charlotte Sound survey has been conducted in July-August in 2003, 2004 and in odd years since 2005. All the synoptic surveys follow a random depth stratified design. The survey area is divided into 2 km by 2 km blocks and each block is assigned to one of four depth strata based on the average bottom depth in the block. The four depth strata for the QCS survey are 50 – 125 m, 125 – 200 m, 200 – 330 m, and 330 – 500 m. Each year blocks are randomly selected within each depth strata. In addition, for the purposes of allocating blocks, the QCS survey is divided into northern and southern spatial strata.

The relative allocation of blocks amongst depth strata was determined by modeling the expected catches of groundfish and determining the target number of tows per stratum that would provide the most precise catch rate data for as many species as possible.

Survey index of abundance – Surveys, swept area analysis

For all surveys, a swept area estimate of biomass in any year *y* was obtained by summing the product of the CPUE and the area surveyed across the surveyed strata *i*:

$$B_y = \sum_{i=1}^{k} C_{y_i} A_i = \sum_{i=1}^{k} B_{y_i} \qquad \text{... Eq. 1}$$

where C_{y_i} = mean CPUE density (kg/km^2) for Pacific Cod in stratum *i*

A_i = area of stratum *i* (km^2), and

B_{y_i} = biomass of Pacific Cod in stratum *i* for year *y*.

k = number of strata

CPUE $\left(C_{y_i}\right)$ for Pacific Cod in stratum *i* for year *y* was calculated as a density in kg/km^2 by

$$C_{y_i} = \frac{\sum_{j=1}^{n_{y_i}} \left(W_{y_i j} \Big/ D_{y_i j} w_{y_i j} \right)}{n_{y_i}} \qquad \text{... Eq. 2}$$

where $W_{y_i j}$ = catch weight (kg) for Pacific Cod in stratum *i* for year *y* and tow *j*

$D_{y_i j}$ = distance travelled (km) by tow *j* in stratum *i* for year *y*

$w_{y_i j}$ = net opening (km) by tow *j* in stratum *i* for year *y*

n_{y_i} = number of tows in stratum *i*

The variance of the survey biomass estimate V_y for Pacific Cod in year *y* is calculated in kg^2 as follows:

$$V_y = \sum_{i=1}^{k} \sigma_{y_i}^2 A_i^2 \Big/ n_{y_i} = \sum_{i=1}^{k} V_{y_i} \qquad \text{... Eq. 3}$$

where $\sigma_{y_i}^2$ = variance of CPUE (kg^2/km^4) for species *s* in stratum *i*

V_{y_i} = variance of Pacific Cod in stratum *i* for year *y*

The CV for Pacific Cod for each year *y* was calculated as follows:

$$CV_y = \frac{\sqrt{V_y}}{B_y} \quad \text{... Eq. 4}$$

One thousand bootstrap replicates with replacement were constructed from the survey data to estimate bias corrected 95% confidence regions for each survey year (Efron 1982).

COMMERCIAL ANNUAL MEAN WEIGHT DATA

The methodology for calculating the mean weight of Pacific Cod from commercial vessels for the years 1956-2012 is presented in Appendix C.

The methods presented in Appendix C differ for Area 5CD and Area 5AB, following the recommendations of the review committee at the January 2014 Centre for Science Advice Pacific Region (CSAP) review meeting, where the first draft of this Research Document was reviewed.

Just before the January 2014 meeting, it was discovered that the query for the extraction of the commercial length samples from the biological database (GFBio) was flawed (see Appendix C). It was also discovered that inadequate sample sizes had been used in the calculation of annual mean weights in Area 5AB for recent years.

Taking results of sensitivity analyses into consideration, the CSAP review committee recommended proceeding with the Area 5CD assessment model for generating catch advice using the flawed query. The committee concluded that estimates of biomass and recruitment were informed by catch, survey and CPUE data more than by the mean weight data. Figures D6 and D7 (Appendix C) illustrate that the flaw in the query had a near negligible impact on the Base Case estimates of biomass and recruitment when compared with a version of the Base Case model that used annual mean weights based on the corrected length query.

For Area 5AB, however, the committee recommended re-running the model with annual mean weights using all available length samples, based on the corrected length query. This was mainly to address the problem of inadequate sample sizes with which to estimate mean weight and also in recognition that the lack of survey indices for Area 5AB between 1995 and 2003 could result in the mean weight data being the main influence on estimates of biomass and recruitment.

Time series of commercial annual mean weights are presented in Appendix C (Figures C2 and C5). Further exploration on the extraction and analysis of length and weight is recommended as a priority research recommendation.

LENGTH DATA

This assessment does not attempt to analyze length-frequency data in detail, but does present length-frequencies as auxiliary information.

Length-frequencies from commercial vessels for the years 1996-2013 are presented in Appendix D. The sample data were extracted from the GFBio, using the criteria given in Table 7. Note that Table 7 represents the corrected query and does not have the problems discussed in Appendix C for Area 5CD. Examination of the sample length frequencies revealed 7 samples that were coded as being Pacific Cod but the size composition was uncharacteristic of the species. These samples, listed in Table 7, were eliminated from the analysis.

Length data for all Pacific Cod from the Hecate Strait assemblage survey, Hecate Strait Pacific Cod monitoring surveys, Hecate Strait synoptic survey and Queen Charlotte Sound synoptic survey were extracted and are presented in Appendix D. All samples taken on these surveys were taken from unsorted catches, i.e., specimens were not selected based on size or sex.

As a general rule the survey retains smaller fish than the commercial vessels and, in particular, there was evidence of a large proportion of small (< 20 cm) fish in Hecate Strait in 2013 (Figure D1). A visual assessment of the commercial length frequencies for Area 5CD (Figure D2) showed some evidence of smaller fish in 1999, 2003 and 2007. There was no indication of small (< 20 cm) fish in the recent Queen Charlotte Sound synoptic surveys (Figure D3). Commercial length-frequencies from Area 5AB indicated large proportions of smaller fish in 2000 and 2007 (Figure D4).

It should be noted in any visual assessment of commercial length-frequency data that an increase in frequency of small fish could be explained by a large recruitment event, a change in selectivity, the introduction of onboard observers, or an artefact of sampling. Changes in selectivity can result from changes to the fishing gear (e.g., mesh size) or changes in fishing location (e.g., depth).

STOCK ASSESSMENT MODEL

All models presented in this document are Bayesian models implemented in AD Model Builder (Fournier et al. 2012). The models are based on the *Integrated Statistical Catch Age Model* (*iSCAM*), developed by Steven J.D. Martell (Martell et al. 2011). A number of modifications have been made to the code by the first author of this assessment to include delay difference calculations and adapt the code for the purpose of assessing Pacific Cod in BC, as described below. The model in its present formulation is fully described in the present document.

DELAY DIFFERENCE MODEL

The previous two assessments for Pacific Cod in Hecate Strait used a delay-difference model (Deriso 1980; Schnute 1985; Hilborn and Walters 1992). Delay difference models represent an intermediate between aggregated surplus production models and fully age-structured models. The delay-difference structure tracks the effects of recruitment, survival and growth on biomass, without requiring a fully age-structured framework, and can perform well, as long as its major assumptions are met (Hilborn and Walters, 1992). Difference equations, which allow for a time-delay between spawning and recruitment, are used to build population models in discrete time-steps (i.e., 1 year), in which the surviving biomass for next year is predicted from the surviving biomass from last year, after adjusting for growth and adding next year's recruitment. An advantage of delay difference models over simpler production models is that they do not assume constant recruitment over time.

The key assumptions of the delay difference model are:

1. Growth in mean body weight W_a follows the linear relationship described by the Ford-Walford equation, $W_a = \alpha_g + \rho_g W_{a-1}$;
2. Knife edge selectivity, i.e., all fish aged *k* and older are equally vulnerable to the fishing gear; and
3. Constant mortality at age, i.e., all fish aged *k* and older have the same mortality rate.

The delay difference model collapses all the equations needed to fully describe the population's age structure into equations for the total numbers (N_t) and biomass (B_t) at time *t*:

$$B_t = S_{t-1}\left(\alpha_g N_{t-1} + \rho_g B_{t-1}\right) + w_k R_t \qquad \text{... Eq. 5}$$

and

$$N_t = S_{t-1} N_{t-1} + R_t \qquad \text{... Eq. 6}$$

where *S* is survival, given by

$$S_t = e^{-(M+F_t)} \qquad \text{... Eq. 7}$$

where *M* is natural mortality; *F* is the estimated instantaneous fishing mortality rate; α_g and ρ_g are the slope and intercept of the Ford-Walford equation, for all ages > *k*, where *k* is the age at which fish are assumed to become fully vulnerable to fishing; w_k is the weight at *k*; and R_t is the assumed stock-recruit function, here constrained to conform to a Beverton-Holt form with *a* and *b* the constants of this equation (Eq. T10.8). It is here assumed that recruitment to the fishery, survey and spawning stock occurs at age 2 y (i.e., *k* = 2 *y*), as assumed by Sinclair and Starr (2005).

A list of model parameters is given in Table 8. Equilibrium and dynamic equations are given in Tables 9 and 10. Variance parameters and components of the objective function are given in Table 11. Throughout this document, equations documented in Tables 8-11 are preceded by the letter T and the table number (e.g., Eq. T9.1 is the first equation in Table 9). Leading estimated parameters are shown in bold type in Table 8. Fixed parameter values and prior probability distributions are given in the description of the candidate Base Case models.

Sinclair and Starr (2005) initialized the model using an estimated ratio parameter that scaled the biomass in 1956 to unfished equilibrium biomass. This ratio was introduced to avoid the assumption that the stock was in an unfished equilibrium state in 1956. However, an error in the coding for the delay-difference model resulted in inconsistencies in the application of equilibrium mean weight used for initializing the model. Two alternative means of initializing the model while avoiding the unfished equilibrium assumption are: (1) to assume the stock was in an "equilibrium fished" state in 1956 using equations T9.7 – T9.9; or (2) use the same approach as an age-structured model for initializing numbers in the first year (Eq. T10.2 and T10.3). The latter alternative was selected for the purposes of this assessment because it was assumed that stocks were not at equilibrium in 1956.

From 1956-2013, bias-corrected annual recruitments were estimated as the product of an estimated mean recruitment (R_{Avg}, estimated in log space) and bias-corrected annual log recruitment deviations (ω_t), weakly constrained to a normal distribution with $\omega_t \sim N(0,2)$. A separate estimated log mean recruitment $\ln(R_{\text{Avg\_init}})$ and estimated vector of eight years of log deviates (age 3 – age 10; ω_{t_init}), with natural mortality used to calculate survival, was used to fill the first year of the numbers-at-age matrix (Eq. T10.2 and T10.3). The number of fish in the first year was then calculated as the sum of numbers at age in the first year. For the years 1957-2013, annual numbers of fish (N_t) were calculated using delay difference equations (Eq. T10.3). Biomass in the first year was calculated as the sum over ages of the product of numbers-at-age and the weight-at-age, with the latter derived from the von Bertlanffy growth parameters (Table 8). Delay difference equations were used to calculate annual biomass (B_t) for the years 1957-2014 (Eq. T10.4), with log recruitment anomalies in the 2014 projection year drawn from a normal distribution, i.e., $\omega_t \sim N(0,\sigma_R)$.

Conditioning the model

The model has some key formulation differences compared to the formulation used by Sinclair and Starr (2005). The 2005 model was conditioned on a qualified effort series, derived from the total catch and catch per unit effort (CPUE) series:

$$E_t = \frac{C_t}{CPUE_t} \qquad \text{... Eq. 8}$$

where the CPUE was calculated using catch and effort data from key fishing locations (Appendix B, CPUE Analysis *D*), while catch was the total estimated catch from the whole of Area 5CD (Table 1). Annual fishing mortality rates (F_t) in the model were then calculated as a function of the qualified effort, i.e.,

$$F_t = q_c E_t \qquad \text{... Eq. 9}$$

where q_c is an estimated parameter describing a linear relationship between the qualified effort data and fishing mortality. The model was then fit to the same total catch data from which the effort series was derived, resulting in a degree of circularity in the model conditioning and fitting.

As discussed above and noted by Sinclair (2000) and Fournier (1983), there are a number of problems with assuming a constant, linear relationship between fishing effort and fishing mortality over time for this fishery. These problems include the large changes in the management regime that ranged from an unrestricted fishery prior to 1992, to the introduction of total allowable catches (TACs) and then IVQs (1997-present). In addition, there have been gear changes including several increases in mesh size, which cumulatively have affected the underlying relationship between commercial CPUE and abundance, and the relationship between fishing effort and fishing mortality. Changes in fishing behaviour also bear consideration, as some fishing masters report active avoidance of Pacific Cod due to quota constraints since the reduction in TAC in the 2000 fishing year (Table 4). This is because reaching or exceeding allowable catch limits for Pacific Cod can reduce opportunities to fish for other co-occurring species for which vessels also hold quota.

The current assessment relaxes the dependence of model results on the commercial CPUE time series by estimating annual log fishing mortality rates directly, rather than calculating fishing mortality as a function of effort and the estimated q_c parameter (Eq. 9). The current model is fit to observed catch data, observed mean weight data and three indices of abundance: the Hecate Strait Multispecies Assemblage Survey; the Hecate Strait Synoptic Survey, and a shortened time series of commercial CPUE data. The CPUE time series spans the period 1956-1995, the year before the introduction of 100% observer coverage in the fishery, and resulting improvements in estimates of discards and general data reliability. In this formulation it must be assumed that catches are known with little to no error, while it is assumed there is observation error in the commercial CPUE data. This assumption is the opposite of the assumption of Sinclair and Starr (2005), where it was assumed the effort data derived from the CPUE data were known without error, and observation error was admitted into the fit to the catch data.

Objective function components

Variance parameters and objective function components are listed in Table 8. The objective function in the delay difference model contained five major components:

1. the negative log-likelihood for the relative abundance data;

2. the negative log-likelihood for the catch data;
3. the negative log-likelihood for the mean weight data;
4. the prior distributions for model parameters, and
5. three penalty functions that:
    - (i) constrain the estimates of annual recruitment to conform to a Beverton-Holt stock-recruit function (T11.14);
    - (ii) weakly constrain the log recruitment deviations to a normal distribution; and
    - (iii) weakly constrain estimates of log fishing mortality to a normal distribution (~*N*(ln(0.2), 4.0)), to prevent estimates of catch from exceeding estimated biomass.

Tests showed the model was insensitive to changes in the penalty function parameters, indicating that the other likelihood components and prior probability distributions were the most important contributors to the objective function.

Indices of abundance

The abundance indices were treated as relative abundance indices, assumed to be directly proportional to the biomass with lognormal errors. The survey catchability parameter for each survey q_j was treated as an uncertain parameter, with the conditional maximum posterior density (MPD) estimate of q_j used in the objective function (Eq. T11.5 – T11.8). In Eq. T11.6, the parameter $\bar{z}_j$ represents the maximum likelihood estimate of $\ln\left(q_j\right)$, conditional on other model parameters, with n_j the number of observations in index *j* (Walters and Ludwig 1994).

Catch data

The model was conditioned on total catch, with annual log fishing mortality rates for the bottom trawl fishery estimated directly. Estimated fishing mortality rates (F_t) were then used to predict catch using the Baranov catch equation (Eq. T10.6). Log residuals (Eq. T11.9) were assumed to be normally distributed with fixed standard deviation σ_C (Eq. T11.10).

Mean weight

Predicted annual mean weight ($\hat{\bar{W}}_t$) was calculated using Eq. T10.7. Log residuals (Eq. T11.11) were assumed to be normally distributed with fixed standard deviation σ_W (Eq. T11.12).

Recruitment

Bias-corrected annual recruitment (Eq. T10.5) was estimated as the product of estimated mean recruitment (R_{Avg}) and estimated annual deviations (ω_t), with both parameters estimated in log space. Predicted recruits ($\hat{R}_t$) were assumed to come from Beverton-Holt stock-recruit function (T10.8). Log recruitment residuals (Eq. T11.13) were assumed to be normally distributed with standard deviation σ_R (Eq. T11.14).

Sinclair and Starr (2005) included an environmental correlate into the stock-recruit relationship, linking recruitment anomalies to Prince Rupert Sea Level anomalies (after Sinclair and Crawford 2005). Sinclair and Starr (2005) reported that the effect of including the environmental correlate made very little difference to estimates of biomass. Unpublished analyses by the authors of the current assessment suggested that model estimates of biomass and recruitment were most strongly influenced by catch and commercial annual mean weight data; and that incorporating a parameter relating the stock-recruit function to an updated time series of air pressure adjusted Prince Rupert sea level data (Figure 55) simply resulted in a shift in estimated recruitment anomalies, resulting in almost identical estimates of biomass and recruits. For this reason, the present assessment does not incorporate the Prince Rupert sea level data. A comprehensive re-analysis of alternative hypotheses for drivers of productivity for Pacific Cod recruitment, including re-evaluation of the relationship between Prince Rupert sea level and recruitment is recommended as a future research priority.

Variance components and weighting of index data

Variance components of the delay difference model implemented within the *iScam* modelling framework (Martell et al. 2011) were partitioned using an errors in variables approach. The key variance parameter is the inverse of the total variance φ^{-2} (i.e., total precision). This parameter can be fixed or estimated, and was fixed here. The total variance is partitioned into observation and process error components by the model parameter ρ, which represents the proportion of the total variance that is due to observation error (Punt and Butterworth 1993, Deriso et al. 2007).

The equation for the observation error component of the total variance (σ_O) is given in Eq. T11.1, while the process error term, σ_R is given in Eq. T11.2. The process error term σ_R enters the objective function in the log likelihood function for the recruitment residuals (Eq. T11.14). In cases when the index of abundance data are informative about absolute abundance (e.g., an acoustic survey), one or both of these parameters, φ^{-2} and ρ, may be estimable. In practice, however, one or both of these parameters usually must be fixed.

It was not possible to obtain plausible estimates of the variance term φ^{-2} for the Base Case model described below. Any attempt to estimate φ^{-2} resulted in estimates of σ_R close to 2.0 (Eq. T11.1) and estimates of σ_O close to 1.5 (Eq. T11.2), with extremely poor fits to the indices of abundance, particularly the commercial CPUE data. It was therefore necessary to fix φ^{-2} and ρ to give fixed values of σ_O and σ_R. Model outcomes were very sensitive to the value of σ_O, mainly as a result of its influence on the goodness of fit to the commercial CPUE data and the 2013 Hecate Strait Synoptic Survey observation. We perform a number of sensitivity tests that evaluate the consequences of the assumed fixed values of φ^{-2} and ρ .

The overall observation error term σ_O influences the fit to all indices of abundance through its contribution to $\sigma_{j,t}$, the standard deviation of log observation residuals for each index *j* in survey year *t* in the log-likelihood function (Eq. T11.8). For a theoretical assessment with only one index of abundance with equally weighted observations, $\sigma_{j,t}$ would be equal to σ_O for all observations. Commonly, however, there are multiple surveys available. Within a given survey, annual coefficients of variation ($CV_{j,t}$) for each observation may also differ from year to year, due to annual sampling differences (e.g., sample size, spatial effects, etc.). It is therefore desirable to weight each observation according to its $CV_{j,t}$, where a low $CV_{j,t}$ for a given observation gives it a higher weight (and lower standard deviation in the objective function). This is implemented multiplicatively using Eq. T11.3, where the $c_{j,t}$ term allows each observation to be weighted relative to the total observation error σ_O. In this case, $c_{j,t}$ is simply obtained from the inverse of $CV_{j,t}$ (Eq. T11.4). For consistency with the use of an overall observation error term applied to all indices of abundance, the vector of $c_{j,t}$ terms was normalized across all surveys by dividing by the mean value of $c_{j,t}$. This choice had the effect weighting each survey observation consistently across all three datasets.

In Eq. T11.4, annual coefficients of variation ($CV_{j,t}$) were derived from bootstrapping the swept area estimates for the Multispecies Assemblage and Synoptic Surveys, using the procedure described in Eqs. 1-4. Annual CVs were not available for the commercial CPUE data, which were obtained from a simple arithmetic approach described in Appendix B. A CV of 0.25 was assumed for each observation in the commercial CPUE data. This was a subjective decision intended to allow the model to fit to the commercial CPUE data without overweighting them. Model sensitivity to this assumption was tested.

A number of authors have noted that there is little consensus on the best approach to managing the relative weighting of multiple survey indices, and that there is always a degree of subjectivity in the choice of weighting strategy (e.g., Francis 2011, McAllister et al. 2001). In particular, there is no objective means of deciding how well a model should fit to commercial CPUE data, given that there is no independent means of knowing the degree to which commercial CPUE data are proportional to the underlying biomass. Commercial fisheries do not sample populations randomly; catchability and selectivity are unlikely to be constant through time; and spatial effects can impact the underlying relationship between CPUE and abundance (Hilborn and Walters 1992). Surveys are assumed to be proportional to abundance by virtue of survey design, however this assumption too can be vulnerable to various effects.

Francis (2011) reviewed some approaches to weighting abundance indices in fisheries stock assessment and advised against subjective down-weighting of commercial CPUE data. He described a two-stage approach to weighting some or all of the datasets with the intention of making data weights more consistent with model output, i.e., satisfying a statistical fit criterion. He proposed a survey-specific weighting term, set so that the standard deviation of normalized Pearson residuals (SDNR) for each index of abundance dataset is equal to about 1.0 (Francis 2011).

In the current assessment, adopting an iterative re-weighting approach similar to that reported in Francis (2011) would necessitate introducing a third, survey-specific weighting term to the calculation of $\sigma_{j,t}$. That is, $\sigma_{j,t}$ would be composed of σ_O, $c_{j,t}$, and a survey-specific weighting term w_j that would bring SDNR close to 1.0 (Francis 2011). Given that both σ_O and the commercial CPUE $CV_{j,t}$ terms were already fixed at subjectively-determined values, and that $c_{j,t}$ was already normalized across surveys, it seemed an unwarranted addition to introduce another fixed weighting term. Francis (2011) stated that the overall goal is a stock assessment that fits all indices of abundance well, and that the SDNR provides a means of judging whether that is the case. However, expert judgment can also be employed (McAllister et al. 2001).

We present sensitivity analyses to the values of fixed variance parameters and suggest that an understanding of the impact of fixed variance assumptions on management advice for Pacific Cod can be obtained without an iterative re-weighting step.

REFERENCE POINTS AND HARVEST CONTROL RULE

The DFO Fishery Decision-making Framework Incorporating the Precautionary Approach (PA) policy (DFO 2009) requires stock status to be characterized using three reference points:

(i) a Reference Removal Rate,

(ii) an Upper Stock Reference point (USR), and

(iii) a Limit Reference Point (LRP).

Provisional values of USR = 0.8 B_{MSY} and LRP = 0.4 B_{MSY} are suggested in the absence of stock-specific reference points. The framework specifies a limit reference removal rate of F_{MSY}. Therefore, we refer to the reference removal rate as the limit removal rate (LRR) throughout this document.

A harvest control rule based on these reference points that is coincident with the choice of LRP, USR and LRR would apply a linear reduction in fishing mortality as the stock falls below the USR, and would cease fishing when the stock reaches the LRP (but see Cox et al. 2013). This is illustrated for a hypothetical stock in Figure 9, where the USR and LRP are shown as vertical lines and the removal rate is shown as a blue line. We make the observation that the rate at which the fishing mortality should be reduced is unspecified in the PA policy, but is usually depicted as a linear ramp between the USR and LRP (Figure 9).

As already noted, large uncertainties in the productivity parameters natural mortality (M) and steepness of the stock-recruit relationship (h) have resulted in substantial uncertainties in MSY-based reference points for Hecate Strait Pacific Cod in previous assessments (Sinclair and Starr 2005). Given uncertainty in productivity parameters for this stock, Sinclair and Starr (2005) suggested using alternative reference points based on the reconstructed history of the stock. They recommended the Limit Reference Point to be the minimum spawning biomass from which the stock recovered to above average levels. This was estimated to have occurred in 1971 (i.e., LRP = B_{1971}). Sinclair and Starr (2005) suggested long-term average Biomass (B_{Avg}) as a candidate proxy Upper Stock Reference and long-term average harvest rate (U_{Avg}) as a proxy for the reference removal rate.

Sinclair and Starr (2005) acknowledged that the absolute estimate of biomass in 1971 is dependent on model formulation (e.g., see Figure 7), but found that most model formulations agreed that 1971 was the year in which the stock was lowest and subsequently recovered to above average levels. Therefore, they recommended the LRP be set at B_{1971} estimated by the assessment model, rather than the absolute 1971 biomass estimated in their specific stock assessment. The Groundfish Subcommittee of PSARC (Fargo 2005) subsequently recommended the use of B_{1971} as the LRP for the Hecate Strait stock. While there is no precedent for reference points in Queen Charlotte Sound, the minimum stock size from which the biomass was estimated to have recovered in this assessment occurred in 1985. B_{1985} was therefore proposed as the LRP for Queen Charlotte Sound. During the December 2014 review of the Area 5AB portion of this assessment, consensus was reached to exclude all biomass-based reference points from management advice for the Area 5AB stock. This is discussed in a later section.

We note that Sinclair and Starr (2005) and the subsequent PSARC proceedings document (Fargo 2005) referred to reference points based on average estimated biomass and fishing mortality variously as "historical", "empirical" and "observation-based", while referring to MSY-based reference points as "model-based". In our opinion, all of the reference points described thus far are model-based, since estimates of historical biomass and harvest rates are conditional on model-assumptions. We therefore prefer to use the terms "MSY-based" and "Historical" to distinguish between the two types of reference points.

Based on the recommendations of the 2005 Scientific Review Committee (Fargo 2005), we recommend continued use of historical-based reference points for the present assessment cycle. However, we note that the recommendation of Fargo (2005) was unclear as to whether the calculation of average biomass and fishing mortality should continue to be fixed for the period 1956-2004, or whether the average should be updated to include recent years. In a later section, we show that there is little difference between the estimated average biomass for the period 1956-2004 compared to the period 1956-2012. For consistency and stability, we suggest continuing to use averages based on the shorter period 1956-2004.

A list of candidate reference points to use in decision tables for Pacific Cod is shown in Table 12. In addition to the LRR, LRP and USR discussed above, two benchmark measures are also included: (i) F_{2013}; and (ii) B_{2014}. These will be used in the decision tables to show whether:

(i) fishing mortality is projected to increase or decrease under alternative 2014 projected catch levels; and

(ii) whether biomass is projected to increase or decrease under alternative 2014 projected catch levels. Estimates of other candidate reference points, based on MSY calculations; and historical averages based on a longer time period are presented for comparison but are not used in decision tables.

The list of performance measures that will be used in decision tables for the Pacific Cod stocks in Hecate Strait (Area 5CD) and Queen Charlotte Sound (Area 5AB) is given in Table 13. Biomass-based performance measures were calculated as projected 2015 biomass relative to reference points, under alternative 2014 projected catch levels (Area 5CD only). Fishing mortality-based performance measures were calculated as projected 2014 fishing mortality relative to the reference points, under alternative 2014 projected catch levels.

We did not explore any alternative reference points in this assessment (e.g., reference points based on spawning biomass per recruit; Clark 1991), but recommend exploration and simulation-testing of alternatives in the context of a feedback simulation analysis.

BRIDGING ANALYSIS

In Appendix A we present a bridging analysis, beginning with a model that emulated the results of the 2005 stock assessment with fixed parameters, through steps that: updated the data streams to 2013; examined the effects of model reconfiguration; and illustrated the effects of fixing variance terms. A bridging analysis provides a means of documenting the transition from the approach used by Sinclair and Starr (2005), and aids in understanding the underlying causes of changes to the stock reconstruction and estimates of key parameters. We present a bridging analysis for the Hecate Strait fishery only, because the Queen Charlotte Sound stock has not been successfully assessed previously. For brevity, we do not present the full suite of sensitivity analyses that were explored but list key steps leading up to development of the candidate Base Case models.

The bridging steps showed that estimates of productivity, fishing mortality and fishery reference points for this stock are strongly dependent on the goodness of fit to the index of abundance data. In particular, outcomes were strongly dependent on the degree to which peaks in 1974 and 1987 commercial CPUE data are fit. This implies that estimates of productivity are dependent on the degree to which it is assumed the commercial CPUE data are representative of abundance. As noted by McAllister et al. (2001) and Francis (2011), there is no objective means of determining how to weight this index of abundance, given well-known concerns about representativeness of fishery-dependent abundance indices.

Therefore, we made a subjective decision to select a Base Case model that provided a visually good fit to the commercial CPUE index of abundance, without fitting to the extreme values. We provide further sensitivity analyses in a later section. The MSY-based reference points were strongly influenced by the goodness of fit to the commercial CPUE data, supporting the decision to retain reference points based on historical reconstruction of biomass and fishing mortality.

BASE CASE MODELS

The Base Case models for both management Areas 5AB and 5CD are based on Step B1a in the bridging analysis (Appendix A). Survey indices of abundance (and CVs) are given in Table

14. Commercial CPUE data are given in Appendix B (Table B5; Analysis D for both Areas 5CD and 5AB). Prior probability distributions and fixed input parameters are provided in Table 15.

Attempts to estimate the total precision φ^{-1} resulted in estimates of σ_R close to 2.0 (Equation T11.1), estimates of σ_O close to 1.5 (Equation T11.2), and extremely poor fits to the indices of abundance, particularly the commercial CPUE data. We therefore made the choice to fix the variance parameters in the model to give $\sigma_R = 0.8$ and $\sigma_O = 0.25$, which improved the fit to the index data. Several sensitivity analyses were done to test the impacts of these assumed fixed values.

PRIOR PROBABILITY DISTRIBUTIONS

Prior probability distributions for the Area 5CD and 5AB Base Case models are shown in Figure 10 and Table 15.

Broad, uniform prior probability distributions were used for $\ln(R_0)$, $\ln(R_{Avg})$, $\ln(R_{Avg\_init})$ and $\ln(q_{CPUE})$, where the subscript CPUE indicates the commercial CPUE data from 1956-1995. These uniform distributions reflect our ignorance the scale of the population.

A Beta distribution was used for steepness with shape parameters that resulted in a distribution with mean = 0.7 and SD = 0.15. These parameter choices resulted in a distribution with almost no probability density for values less than 0.2, implying that no transformation was necessary (Figure 10). Sinclair and Starr (2005) fixed steepness at 0.75 in one of their "preferred" scenarios. In their other "preferred" scenario, the MPD estimate of steepness was 0.53. The prior probability distribution chosen here encompasses both of these values. A sensitivity analysis was done for both areas with a uniform distribution for steepness between 0.21 and 0.99, with very little impact on posterior estimates of biomass (see below).

A normal distribution was used for $\ln(M)$ with mean = $\ln(0.5)$ and SD = 0.1. Sinclair and Starr (2005) obtained MPD estimates of natural mortality of 0.596 and 0.567 in their two "preferred" scenarios. The bridging analysis provided in Appendix A of this document suggested that natural mortality could be considerably lower, depending on the values of other fixed or estimated parameters. For the base cases presented here, we chose to centre the prior probability distribution a little lower than the MPD values reported by Sinclair and Starr (2005). Model sensitivity to both the mean and the standard deviation of the distribution is presented below.

Normal distributions were used for $\ln(q_A)$ and $\ln(q_S)$, where the subscripts *A* and *S* indicate the Hecate Strait Assemblage Survey and Synoptic Survey respectively (Table 15). Normal distributions centred on $\ln(1.0)$ were selected because the survey estimates of biomass were derived from swept area analysis (Eq. 1-2) and could therefore reasonably be expected to be some fraction of unity. A large standard deviation was used to reflect ignorance of the scale of the swept area analysis compared with the true biomass. Note there was no Assemblage Survey in Queen Charlotte Sound (Area 5AB). Broad uniform distributions were used for $\ln(q_{CPUE})$, reflecting large uncertainty in the scale of the relationship between commercial CPUE data and true biomass.

A total of 132 model parameters were conditionally estimated in Area 5CD; while 131 parameters were estimated for Area 5AB, which had one fewer survey *q* parameters (Table 15).

RESULTS

AREA 5CD: HECATE STRAIT

The joint posterior distribution was numerically approximated using the Markov Chain Monte Carlo routines built into AD Model Builder (Fournier et al. 2012). Posterior samples were drawn systematically every 50,000 iterations from a chain of length 100 million, resulting in 2,000 posterior samples (the first 1,000 samples were dropped to allow for sufficient burn-in). Convergence was diagnosed using visual inspection of the trace plots (Figure 11) and visual examination of autocorrelation in posterior chains (Figure 12). Autocorrelation was minor for most parameters, except for $\ln(R_{\mathrm{Avg\_init}})$, for which autocorrelation was quite strong. This likely reflects lack of information in the data about this parameter. Overall, there was no strong evidence for lack of convergence, although the model occasionally estimated very large values for $\ln(R_0)$, possibly because of this parameter was confounded with steepness (h) (Figure 13). Very high estimates of $\ln(R_0)$ were obtained when h was estimated to be very low (Figure 13). Survey catchability parameters were positively correlated with each other and negatively correlated with $\ln(M)$, implying that there is limited information in the data to distinguish between a small productive population or a larger, less productive population (Figure 13).

Maximum posterior density (MPD) model fits to the three indices of abundance are shown in Figure 14. Model-estimated indices of abundance followed the general trends of all three observed trends, although they failed to reach most of the peaks in the respective datasets. As previously discussed above and in the bridging analysis (Appendix A), model outcomes, especially estimates of productivity parameters, were very sensitive to the goodness of fit to the indices of abundance, particularly peak commercial CPUE observations and the 2013 Synoptic Survey observation (Table A5). We consider the goodness of fit to the indices of abundance to be a primary driver of uncertainty in this assessment and present further sensitivity analyses in a later section.

Posterior probability distributions of estimated parameters are shown in Figure 15. The median, 2.5th percentile and 97.5th percentile posterior parameter estimates, and maximum posterior density (MPD) estimates, are given in Table 16. With the exception of steepness, the posterior estimates did not appear to be strongly influenced by the prior probability distributions. The posterior probability distribution for steepness was very similar to the prior probability distribution, implying that there is little information about this parameter in the available data. Sensitivity to the prior distribution assumed for steepness is tested in a later section. Posterior probability estimates of $\ln(M)$ tended to be lower than the prior values, although the right-hand tail of the posterior distribution did overlap with the left-hand tail of the prior distribution (Figure 15). We have already noted that posterior estimates of M were strongly influenced by the fit to the index of abundance data (Table A5), which likely has a stronger influence on estimates of M than the prior probability distribution.

Normal prior probability distributions were used for the log catchability parameters $\ln(q)$ for the Hecate Strait Assemblage and Synoptic Surveys (Figure 10). These prior probability distributions did not appear to strongly affect the posterior estimates, with the posterior distribution far to the left of the prior distribution in both cases (Figure 15).

The Hecate Strait Base Case model predicted the stock to be on an increasing trajectory (Figure 16; Table 17). The median posterior estimate of 2013 biomass was below the median Upper Stock Reference (USR), and above the median Limit Reference Point (LRP), i.e., in the Cautious Zone (DFO 2009). The 95% posterior credibility interval for biomass was very broad for recent years, with substantial parts of the interval both above the USR and below the LRP since 2009. Projected 2014 biomass is projected to be above the 2013 biomass. The estimate of B_0 was highly uncertain, with the posterior median estimated to be almost 35,000 tonnes, just below the estimated maximum biomass in 1965 (Figure 16; Table 16). However, the 95% credibility interval extended far above the range of estimated historical biomasses.

Posterior median estimates and 95% credibility interval of age-2 recruits are shown in Figure 17 and Table 18. Peaks in recruitment were estimated to have occurred in 1964, 1972 and 1986. Posterior median recruitment is estimated to have been below the long-term median recruitment since 1993, with the exception of apparent stronger recruitment in 2002. The 95% posterior credibility intervals since 2008 are reasonably broad, with considerable uncertainty around the estimate of 2013 recruitment. This is expected since there is no information in the data about the strength of this year class.

Posterior estimates of fishing mortality are shown in Figure 18 and Table 19. The median posterior estimate of fishing mortality is estimated to have peaked in 1991 at 0.513 y^{-1}. Fishing mortality has been estimated to have been well below the LRR, since 1998. Median posterior fishing mortality rates are estimated to have been less than 0.1 y^{-1} since the reduction in TAC in 2001 (Figure 18 and Table 19).

Reference Points

Posterior estimates of F_{2013} and B_{2014} are shown in Figures 19 and 20, and Table 20. Fishing mortality in 2013 was low compared to the historical period, with the posterior median estimated to be 0.052 y^{-1}.

As discussed in the previous section, we used reference points based on the reconstructed time series of stock biomass and fishing mortality, rather than MSY-based reference points. Reference points and performance measures were summarized in Tables 12 and 13. Boxplots of the posterior distributions of all the reference points from Table 13 are shown in Figure 20. Percentiles of the posterior probability distributions are given in Table 20.

Estimated reference points based on fishing mortality are shown in Figure 20a and Table 20.. Estimates of F_{MSY} were estimated to be extremely uncertain, with the 95% posterior credibility interval ranging from 0.148 to 0.527 y^{-1}. Both estimates of average historical fishing mortality, based on the short (1956-2004) and long (1956-2012) time series, were estimated to be lower than F_{MSY} and were considerably more precise (Figure 20a). There was very little difference between the estimated historical average fishing mortality for the short period compared with the long period, although the latter was slightly lower (Figure 20a, Table 20).

Estimated reference points based on biomass are shown in Figure 20b and Table 20. As discussed above, there was considerable uncertainty in the projected estimate of 2014 biomass, due to large uncertainty in 2013 recruitment (Figure 17). The MSY-based reference points, B_{MSY} (and therefore the fractions $0.8B_{MSY}$ and $0.4B_{MSY}$) were characterized by extremely long tails that extended well above the 95% posterior credibility interval. The posterior median estimate of the Limit Reference Point of B_{1971}, was 12,182 t (Table 20). The posterior median estimate of the Upper Stock Reference was 19,258 t.

We suggest that the large uncertainty in estimates of MSY-based reference points (Figure 20, Table 20), in addition to their sensitivity to estimates of productivity parameters (Table A5, Figure A16), provides further support to avoid their use in developing catch advice for this stock.

AREA 5AB: QUEEN CHARLOTTE SOUND

Although Area 5AB has been managed as a separate stock there is little evidence that Pacific Cod in Area 5AB and 5CD constitute different biological stocks (Appendix E). While there are operationally valid reasons for maintaining spatial management, necessary for the functioning of the multi-species integrated groundfish fishery, the possibility that Pacific Cod in Areas 5AB and 5CD are not separate biological stocks presents challenges to the identification and interpretation of biological reference points (the same is true of Area 5CD, although a larger proportion of the biomass is estimated to occupy Area 5CD). Also, there have been no recent successful assessments of Area 5AB Pacific Cod that could have led to the development of agreed upon reference points. The review committee at the December 2014 meeting did not find any of the proposed biomass-based reference points satisfactory (B_{MSY}-based or reference points based on estimated historical biomass). Therefore, no biomass-based reference points are presented for the Area 5AB stock. This is discussed in further detail below.

Posterior samples were drawn systematically every 25,000 iterations from a chain of length 50 million, resulting in 2,000 posterior samples, with the first 1,000 samples excluded from the sample to allow for burn-in. The MCMC algorithm did not converge as well as the Area 5CD analysis, and there was autocorrelation in the posterior parameter estimates evident in the chains (Figures 21 and 22). Like the results for Area 5CD, autocorrelation was worst for the parameter $\ln(R_{\mathrm{Avg\_init}})$. Survey catchability parameters were positively correlated with each other and negatively correlated with $\ln(M)$, implying that there is limited information in the data to distinguish between a small productive population or a larger, less productive population (Figure 23).

Maximum posterior density (MPD) model fits to the two indices of abundance are shown in Figure 24. Model-estimated indices of abundance followed the general trends of both observed trends, but failed to fit to the maximum peaks in both respective datasets. As for Area 5CD, we consider the goodness of fit to the indices of abundance to be a primary axis of uncertainty for this delay-difference model assessment and present sensitivity analyses in a later section.

Posterior probability distributions of estimated parameters are shown in Figure 25. The median, 2.5th percentile and 97.5th percentile posterior parameter estimates, and MPD estimates, are given in Table 21. With the exception of steepness and $\ln(q)$, the posterior estimates did not appear to be strongly influenced by the prior probability distributions. Posterior probability estimates of steepness and $\ln(M)$ tended to be lower than the prior values, although the posterior distributions overlapped with the priors (Figure 25). A normal prior probability distribution was assumed for the catchability parameter, $\ln(q)$, for the Queen Charlotte Sound Synoptic Survey (Table 15). This prior distribution appeared to strongly affect the posterior estimates, despite the prior being fairly broad (Figure 25).

The Queen Charlotte Sound Base Case model reconstructed the current stock to be on a flat trajectory, below the historical average (Figure 26). The 95% posterior credibility interval for biomass was broad for recent years. Projected 2014 biomass is shown in red in Figure 26 and is projected to be slightly above the 2013 biomass. The estimate of B_0 was less uncertain than that obtained for Area 5CD, with the posterior median value estimated to be 7,046 t (Figure 26; Table 21).

Posterior median estimates and 95% credibility interval of age-2 recruits, and log recruitment anomalies, are shown in Figure 27 and Table 23. Maximum median estimates of recruitment occurred in 1964, 1973 and 1987. Posterior median recruitment is estimated to have been below the long-term median recruitment since 1993.

Posterior estimates of fishing mortality are shown in Figure 28 and Table 24. The median posterior estimate of fishing mortality is estimated to have peaked in 1993 at 0.701 y^{-1}. The median posterior estimate of 2013 fishing mortality is estimated to have been 0.290 y^{-1}, close to the long-term average of 0.269 y^{-1} (Table 25 and Figure 29).

We note that the period of estimated low biomass beginning in 1996 (Figure 26) is coincident with the end of the commercial CPUE time series data and the introduction of low quotas for this stock (Figure 3; Table 3). Importantly, there is a large shift in the length composition data before and after 1998 (Appendix C, Figure C1). This is due to the introduction of mandatory onboard observers in 1996 and the beginning of sampling of the entire size composition in the catch, instead of only fish that were landed ("Keepers"). The lack of survey data between 1995 and 2003 implies that catch and mean weight data are the principle sources of information for stock size and recruitment in recent years. Both of these datasets have been strongly influenced by management changes (introduction of low quotas and onboard observers). We therefore urge caution in interpreting the estimates of low biomass and recruitment in recent years as evidence of a change in productivity of the stock in Area 5AB.

We recommend that future efforts be made to combine the datasets from Area 5CD and Area 5AB into a single stock assessment to help alleviate some of the data concerns with Area 5AB. As there is no strong evidence that the population in Area 5AB is distinct from that in Area 5CD (Appendix E), a combined assessment will likely be justified, even if quotas are still implemented separately for the two management areas.

Reference Points

Alternative reference points based on estimates of average historical biomass, similar to those adopted in Area 5CD, were explored. However, these historical reference points were problematic for Area 5AB because the period chosen (1956-2004) occurred during a time when fleet behaviour differed significantly from recent years. Currently, many vessels in Area 5AB actively avoid Pacific Cod due to low quotas. This was not the case in the historical period, when vessels actively targeted Pacific Cod and no quota was in place. While this was also true for Area 5CD, the effects on model results of changes in management on biomass estimates in Area 5AB were stronger for two main reasons:

(i) there was no index of abundance to bridge between the pre- and post-1996 periods in Area 5AB, meaning that estimates of biomass were strongly affected by the reductions in catch following the introduction of quotas; and

(ii) there was an abrupt shift in the commercial length data (used to calculate annual mean weights) due to the introduction of observers (Appendix C). Sensitivity analyses showed that the Area 5AB assessment was much more strongly influenced by the annual mean weight data in the post-1996 part of the time series than was the Area 5CD assessment. The review committee therefore had low confidence that the model was accurately estimating biomass in the post-1996 period.

Using the post-1996 period to define historical biomass-based reference points, which were thought to be more consistent with recent estimates of biomass, was also problematic. This was because the resulting estimates of average biomass were very low and were considered to be inconsistent with a precautionary decision-making framework. Historical biomass-based reference points were therefore rejected for use in Area 5AB.

Estimated fishing mortality rates were reasonably constant over the whole time series (Table 24 and Figure 28) and were reasonably robust across a range of model assumptions. Therefore, a provisional, model-averaged reference point based on the average estimated fishing mortality for the period 1956-2004 ($F_{avg(1956-2004)}$) was adopted as a provisional LRR until further analyses can be completed. The review committee at the December 2014 CSAP meeting recommended that the current model be updated on a regular basis to re-estimate fishing mortality. The committee also proposed using the biennial QCS survey index as a trigger point for new advice. Specifically, the trigger for action would occur when any additional index point (after 2013) falls below 50% of the mean survey indices prior to the new index point. If this occurs, additional analysis will be required and an updated assessment could be requested (see also Research Needs).

Posterior estimates of F_{2013} are shown in Figure 29 and Table 25.

Proposed reference points and performance measures were summarized in Tables 12 and 13. Boxplots of the distribution of *F*-based reference points from Table 13 for Area 5AB are shown in Figure 30. Percentiles of the posterior probability distributions of the reference points are listed in Table 25.

Estimated reference points based on fishing mortality (Figure 30a; Table 25) suggest that fishing mortality in 2013 was of a similar magnitude to the rest of the historical period, with the median estimated to be 0.289 y^{-1}. Estimates of F_{MSY} were extremely uncertain, with the 95% posterior credibility interval ranging from 0.155 to 0.553 y^{-1}. Estimates of average historical fishing mortality, based on both the short (1956-2004) and long (1956-2012) time series, were estimated to be similar in magnitude to F_{MSY} but were slightly less variable (Figure 30a; Table 25). As for Area 5CD, there was very little difference between the estimated historical average fishing mortality for the short and long periods (Figure 30a, Table 25).

SENSITIVITY ANALYSES

We present a number of sensitivity analyses to show the influence of fixed parameters and prior probability distributions in the Area 5CD Base Case model. A limited subset of these sensitivities are presented for the Area 5AB Base Case model.

AREA 5CD: HECATE STRAIT

We tested sensitivity of the model outputs to the following assumptions:

1. The prior probability distribution for ln(M);
2. The prior probability distribution for steepness;
3. The assumed fixed value of σR;
4. The assumed fixed value of σW;
5. The effect of including recent (1996-2012) commercial CPUE data as an index of abundance; and
6. The effect of alternative treatment of variance parameters.

Results are presented under these headings below, with Base Case parameter settings provided in Table 15. In all sensitivity runs, posterior samples were drawn systematically every 10,000 iterations from a chain of length 20 million, resulting in 2,000 posterior samples; the first 1,000 samples were dropped to allow for sufficient burn-in.

1. Prior probability distribution for ln(*M*)

Three sensitivity analyses are shown to illustrate the effect of the parameters of the normal prior distribution assumed for ln(*M*):

a. the mean was held at the Base Case value of 0.5 y^{-1}, while the standard deviation was increased to 0.2;

b. the mean was reduced to 0.4 y^{-1} and the standard deviation was held at the Base Case value of 0.1; and

c. the mean was reduced to 0.4 y^{-1} and the standard deviation was increased to 0.2.

Median posterior estimates of M were: (i) 0.323 y^{-1}; (ii) 0.347 y^{-1}; and (iii) 0.300 y^{-1}, compared to the median posterior Base Case estimate of $M = 0.393$ y^{-1}. It therefore appears that the assumed prior probability distribution for natural mortality does influence posterior estimates of M and that the prior used in the Base Case model may have resulted in higher estimates of M than if a less informative prior had been used. Convergence properties appeared to be poor for Case a), with large auto-correlation in several chains. However, convergence properties for Cases b) and c) were the same or better than those obtained for the Base Case model, particularly for Case c) (not shown).

The biomass estimates that resulted from each sensitivity case are shown in Figure 31. There was almost no discernible difference in recent biomass estimates among scenarios for the three cases. However, there were large differences in estimated historical biomasses, with historical biomasses estimated to be smaller than for the Base Case in all three scenarios. Because of this, estimates of current stock status relative to the USR and LRP were different for these three sensitivity cases. We only show results for cases b and c, which had much better convergence properties than case a, in Figure 32. Results show that the stock was estimated to be larger relative to the historical averages as estimates of M declined.

2. Prior probability distribution for steepness (*h*)

Sensitivity to the assumed prior probability distribution for steepness was tested by running the model with a uniform prior for this parameter with lower and upper bounds of 0.21 and 0.99, respectively. Biomass and parameter estimates are shown in Figures 33 and 34, where it can be seen that there was relatively little effect of the prior on steepness on posterior estimates of biomass, although estimates in recent years were slightly lower (Figure 33). The median posterior estimate of B_0 was much larger than the maximum estimated biomass in the time series, and the model showed poor convergence for most parameters. The model's tendency to sample very low estimates of steepness with this prior resulted in some very large estimates of $\ln(R_0)$ and $\ln(R_{\mathrm{Avg\_init}})$ (Figure 34). This result suggests that an informative prior for steepness helped to improve model convergence properties without having a very large influence on biomass estimates (Figure 33).

3. Assumed fixed value of σ_R

Throughout this assessment so far, 0.8 was assumed to be an appropriate value for σ_R, as this stock appears to have had very variable recruitment throughout the history of the fishery. In this sensitivity analysis, we test two alternative fixed values of σ_R: (i) $\sigma_R = 0.4$; and (ii) $\sigma_R = 1.0$. Resulting estimates of historical biomass are shown in Figure 35. As for the steepness sensitivity test, there was very little discernible difference in the estimated historical time series between the Base Case model and the two sensitivity cases. The largest effects were seen in the estimates of B_0 (Figure 35), which showed much lower posterior estimates obtained with $\sigma_R = 0.4$; and much higher and uncertain posterior estimates with $\sigma_R = 1.0$ as a function of the increased recruitment variation.

4. Assumed fixed value of σ_W

Problems with interpreting the mean weight data were discussed in Appendix C. These problems stem from changes over time in the sample sizes of different categories of length data, i.e., sorted and unsorted categories. Concerns about the use of the mean weight data were also recorded in the review of the 2005 assessment (Fargo 2005). This issue was acknowledged by Sinclair and Starr (2005), who noted that the mean weight series was necessary for estimation of model parameters but was down-weighted in the objective function. Given the uncertainties in interpreting this time series and its potential to provide direct information for scaling the population size, we tested model sensitivity to the value of the standard deviation of the mean weight residuals, σ_W. In the Base Case model, σ_W was fixed at 0.2. For this sensitivity test, we set $\sigma_W = 0.4$, applying more down-weighting to the influence of the mean weight data in the objective function.

Estimates of biomass and mean weight were considerably lower as a result of increasing σ_W (Figures 36 and 37). The median estimate of B_0 was also lower, with a smaller credibility interval than the Base Case model. The credibility intervals around estimates of biomass were also narrower for this sensitivity case. Without independent estimates of the mean weight of fish in the fishery, it is difficult to judge how well the mean weight data should be fit.

We note that even the Base Case model had poor fits to the mean weight data during the 1990s, with mean weight consistently under-estimated (Figure 37a). This was estimated to be a period of declining biomass and it is plausible that mean weights of individual fish could have been larger than average if growth were density dependent or if fishermen were discarding a different size range of fish during this period. Growth is assumed to be density-independent in the delay difference model with constant selectivity. Violation of one or both of these assumptions is a possible hypothesis for the poor fits to the mean weights in the 1990s.

The scaling effect of the mean weight data reduced the posterior estimated biomass in a fairly consistent manner throughout the time series. Therefore, current stock status relative to historical average biomass was similar to the Base Case model, but at a lower scale (Figure 36b). However, catch levels in 2014 would be expected to have a greater impact on the projected 2015 biomass in this sensitivity case, because of the lower estimated current biomass.

5. Effect of including recent (1996-2012) commercial CPUE data as an index of abundance;

In Appendix A, we provided rationale for excluding the post-1995 commercial CPUE data as an index of abundance. The main reason was that a shift in management fishing practices could have resulted in some vessels actively avoiding Pacific Cod for parts of the year. Here, we provide a sensitivity test to illustrate the impact of fitting to this index on model outcomes. As for the pre-1996 CPUE data, we assumed an annual CV = 0.25.

The model fit to the trend in the post-1995 commercial CPUE data reasonably well (Figure 38). The estimated trend in recent biomass was very similar to that from the Base Case model (Figure 39). This was likely because the trends in recent survey biomass and commercial CPUE data were largely in agreement (Appendix B). The 95% posterior credibility interval for post-2000 period biomass was slightly narrower than for the Base Case model.

The results of this analysis suggest, *post hoc*, that adding the post-1995 CPUE data did not have a large effect on model outcomes, although we suggest that our reasons for questioning the utility of the data as a useful index of abundance had merit *a priori*.

6. Effect of alternative treatments of weighting the indices of abundance

Appendix A showed that estimates of productivity parameters were very sensitive to the goodness of fit to the commercial CPUE data and to the 2013 Hecate Strait Synoptic Survey data point. In Appendix A, we tested the model sensitivity to two different fixed values of the overall observation error term σ_O. Here we present four alternative approaches affecting the goodness of fit to the indices of abundance, all based on the Base Case model:

a. Improve the goodness of fit to all three indices by setting $\sigma_O = 0.15$;

b. Down-weight the commercial CPUE index by setting annual CV = 0.35;

c. Allow the indices of abundance to "self weight" by evaluating the marginal likelihood of the observations at the conditional maximum likelihood estimate of σ_j using the approach of Ludwig and Walters (1994); and

d. Follow the advice of Francis (2011) and remove the commercial CPUE data altogether to compare model outcomes with the Base Case model.

We describe the four approaches in more detail below then present results.

Alternative a) Set $\sigma_O = 0.15$

The choice to set $\sigma_O = 0.25$ in the Base Case model was arbitrary, based on our experience of previous assessments. Effectively, we assumed that large peaks and troughs in the CPUE data may not necessarily be proportional to peaks and troughs in abundance in those years, and allowed the model to not fit those peaks. These represent subjective assumptions on our part, that we have already showed have an impact on our understanding of current stock size and status (Appendix A). Therefore, in this sensitivity run, we forced the model to fit all three indices of abundance more closely by setting σ_O to a lower value.

Alternative b) Set $CV_{i,j} = 0.35$ for the commercial CPUE data

The commercial CPUE data presented in Appendix B were calculated using arithmetic means, rather than a generalized linear modelling approach. There were therefore no CVs associated with the annual observations. We made the parsimonious assumption that annual CVs were the same for each observation and set them at an arbitrary value of 0.25, based on experience with similar datasets. In this sensitivity case, the influence of the commercial CPUE data was reduced by setting annual CVs to a higher, arbitrary value of 0.35.

Alternative c) Use the conditional maximum likelihood estimate of σ_j

An alternative approach is to allow the variances to "self-weight". In this analysis, we used the approach of Walters and Ludwig (1994) and evaluated the marginal likelihood of the observations at the conditional maximum posterior density (MPD) estimate of σ_j using:

$$L_j = \frac{ss^2}{2(n_j - 1)} \qquad \text{... } Eq.\ 10$$

where ss^2 is the sum of squared differences between log observed and predicted indices of abundance, and n_j is number of observations in each index j. In this sensitivity case, Equation 10 replaces the sum of Eq. T11.8 in the objective function. The self-weighting approach provides a means of removing the need to specify a value for σ_O. However, it does not completely remove the requirement to assume that commercial CPUE provides a (relative) index of abundance.

Alternative d) Remove commercial CPUE data

To further explore the effect of fit to the CPUE data on estimates of productivity parameters, we removed the commercial CPUE data completely. Francis (2011) recommended against subjective down-weighting commercial indices of abundance and suggested instead that uncertainty be characterized by running the model with and without fishery-dependent indices.

Results

Setting $\sigma_O = 0.15$ resulted in an improved fit to all three indices of abundance, in particular the Hecate Strait Synpotic Survey and commercial CPUE data (Figure 40a). Down-weighting the commercial CPUE data resulted in a slightly worse fit to the commercial CPUE data, when compared to the fit obtained from the Base Case model, although the difference was minor (Figure 40b). Incorporation of the conditional MPD estimate of σ_j using Eq. 10 in the objective function worsened the fit to the Hecate Strait Synoptic Survey data, particularly for 2013, but resulted in a minor difference to the fit of the commercial CPUE data (Figure 40c). Finally, removing the commercial CPUE data resulted in very little difference to the fit to the Hecate Strait Synoptic Survey data and a slightly better fit to the Hecate Strait Assemblage Survey data (Figure 40d).

The effect of differences in fit to the survey data had a noticeable effect on posterior estimates of biomass for the stock. Setting $\sigma_O = 0.15$ resulted larger posterior peak biomasses than in the Base Case model (Figure 41a). Posterior estimates of M and steepness were much higher than for the Base Case model (median $M = 0.491$ y^{-1}; median $h = 0.731$). Despite these differences, estimates of recent biomass were close to those from the Base Case model (Figure 41a). The median posterior estimate of B_{1971}, the LRP, was lower than for the Base Case model (Figure 41a). A greater proportion of recent biomass estimates were therefore estimated to have been above the LRP (Figure 41b). However, narrower 95% credible intervals in this sensitivity case resulted in a smaller proportion of the projected 2014 biomass estimates that were above the Upper Stock Reference, and no posterior estimates of 2013 biomass above this threshold (Figure 41b).

Down-weighting the commercial CPUE data had little effect on posterior estimates of biomass for most of the time series, although the 2013 estimate was slightly higher than in the Base Case Model (Figure 42).

Using the conditional MPD estimate of σ_j using Eq. 10 in the objective function resulted in substantially reduced estimates of biomass in the period 2001-2013 (Figure 43). This was largely driven by the very poor fit to recent Synoptic Survey data points (Figure 40c).

Removing the CPUE data altogether resulted in a very different estimated historical biomass trajectory, compared to the Base Case (Figure 44a). Initial 1956 biomass was estimated to be much larger, characterizing large catches in the mid-1960s as a “fishing down” exercise rather than in response to a large early pulse in recruitment. The median posterior estimate of M was slightly higher than for the Base Case model (0.418 y^{-1}), while steepness was estimated to be lower (median $h = 0.609$). Despite large differences in posterior estimated biomass in the early part of the time series, recent estimates were more similar, although the posterior credibility interval was larger than for the Base Case model and the recent median estimates were slightly higher (Figure 44a). Stock status, however, was very different for this scenario, as both the estimated 1971 biomass and historical average biomass were much higher than for the Base Case (Figure 44b). This outcome highlights the problem that even reference points based on historical estimates of fishing mortality can be highly conditional on model assumptions.

Summary: Area 5CD

To summarize this set of sensitivity analyses, posterior estimates of biomass and current stock status relative to historical biomass were most sensitive to the prior probability distribution for log natural mortality (Figure 32); the standard deviation used in the objective function for the fit to the mean weight data (Figure 36); the goodness of fit to the commercial CPUE data (Figures 40a and 41); the goodness of fit to the 2013 Hecate Strait Synoptic

Survey observation (Figures 40c and 43); and the choice to include or exclude the commercial CPUE data (Figures 40d and 44).

In terms of going forward into management advice, we suggest that the sensitivity case using the conditional MPD estimate of σ_j (Figures 40c and 43) can be rejected, given the very poor fit to the Hecate Strait Synoptic Survey data.

We suggest that we cannot further reduce the uncertainty arising from the prior probability distribution for ln(*M*) (Figure 32); the goodness of fit to the mean weight data (Figure 36); or the decision to closely fit (Figures 40a and 41) or exclude the commercial CPUE data (Figures 40d and 44).

AREA 5AB: QUEEN CHARLOTTE SOUND

For brevity, we ran a subset of the above sensitivity analyses for Area 5AB.

1. Prior probability distribution for ln(*M*)

Two sensitivity analyses are shown to illustrate the effect of the prior probability distribution assumed for ln(*M*):

(i) the mean was held at the Base Case value of 0.5 y^{-1}, while the standard deviation was increased to 0.2; and

(ii) the mean was reduced to 0.4 and the standard deviation was increased to 0.2.

Median posterior estimates of *M* were: (i) 0.339 y^{-1}; and (ii) 0.297 y^{-1}, compared to the median posterior Base Case estimate of $M = 0.437$ y^{-1}. As for Area 5CD, it appears that the assumed prior probability distribution for natural mortality does influence posterior estimates of *M* and that the prior used in the Base Case model resulted in higher estimates of *M* than if a less informative prior had been used. Unlike the equivalent sensitivity cases for Area 5CD, convergence for both of these scenarios was poorer than for the 5AB Base Case model.

The resulting biomass estimates are shown in Figure 45. Median posterior biomass estimates were lower across the whole time series for the two sensitivity cases.

2. Prior probability distribution for steepness (*h*)

Sensitivity to the assumed prior probability distribution for steepness was tested by running the model with a uniform prior for this parameter with lower and upper bounds of 0.21 and 0.99, respectively. The resulting posterior biomass estimates are shown in Figure 46. There was relatively little effect of the prior on steepness on posterior estimates of biomass, although estimates in recent years were slightly lower, as for Area 5CD.

3. Assumed fixed value of σ_W

As for Area 5CD, this sensitivity analysis evaluates model sensitivity to the standard deviation of the mean weight residuals, σ_W, which was increased to 0.4 in this scenario.

Estimates of biomass in the earlier parts of the time series were similar to those in the Area 5AB Base Case model. However, while recent median posterior estimates of biomass and credibility interval were very close to those from the Base Case, the credibility interval was much broader (Figure 47), indicating that the annual mean weight data influenced the estimates of recent biomass. See previous section and Appendix C for discussion of bias in the mean weight data in Area 5AB.

4. Effect of alternative treatments of weighting the indices of abundance

Here we present two alternative approaches affecting the goodness of fit to the indices of abundance:

(i) Set $\sigma_O = 0.15$; and

(ii) Allow the indices of abundance to "self weight" by evaluating the marginal likelihood of the observations at the conditional maximum likelihood estimate of σj using the approach of Walters and Ludwig (1994).

Setting $\sigma_O = 0.15$ resulted in a closer fit to both indices of abundance (Figure 48a). Using the conditional MPD estimate of σ_j in the objective function resulted in a very poor fit to the 5AB commercial CPUE data and a slightly worse fit to the Queen Charlotte Sound Synoptic Survey data (Figure 48b).

The effect of goodness of fit to the survey data had a noticeable effect on posterior estimates of biomass for the stock. Setting $\sigma_O = 0.15$ resulted smaller posterior peak biomasses than in the Base Case model (Figure49). Posterior estimates of *M* and steepness were similar to those from the Base Case model (median $M = 0.433\ y^{-1}$; median $h = 0.0.648$). Estimates of recent biomass were much lower than those from the Area 5AB Base Case model (Figure 49).

Using the conditional MPD estimate of σ_j in the objective function resulted in a very different posterior biomass trajectory for the stock in Area 5AB (Figure 50). This was driven by the poor fit to the commercial CPUE data (Figure 50b). Posterior estimates of historical biomass were larger and more uncertain than for the Base Case model and did not feature such pronounced peaks and troughs. Estimates of average historical biomass were therefore higher, resulting in lower and more uncertain posterior estimates of current stock status (Figure 50). Given the poor fit to the commercial CPUE data in this sensitivity case, we consider this scenario to be similar to the "no CPUE" sensitivity case shown for Area 5CD.

5. Effect of including recent (1996-2012) commercial CPUE data as an index of abundance

As for Area 5CD, we provide a sensitivity test to illustrate the effect of fitting to the 1996-2012 commercial CPUE index on model outcomes. As for the pre-1996 CPUE data, we assumed an annual CV = 0.25.

The model fit to the trend in the post-1995 commercial CPUE data reasonably well (Figure 51). The posterior estimated trend in historical biomass was very similar to that from the Base Case model, although there was divergence from Base Case posterior estimates of biomass in the post-1996 period (Figure 52).

Summary: Area 5AB

To summarize this set of sensitivity analyses, posterior estimates of biomass and current stock status relative to historical biomass w ere most sensitive to the prior probability distribution for log natural mortality (Figure 45); the standard deviation used in the objective function for the fit to the mean weight data (Figure 47); and the goodness of fit to the commercial CPUE data (Figure 50).

We suggest that we cannot further reduce the uncertainty arising from the prior probability distribution for ln(*M*) (Figure 45); the goodness of fit to the mean weight data (Figure 47); or the goodness of fit to the commercial CPUE data (Figures 48a,b, 49 and 50).

DECISION TABLES

Performance measures were calculated over a sequence of alternative 2014 projected catch levels and are based on one-year projections to 2015. Projected recruitment anomalies in 2015 were drawn randomly from a normal distribution, N~$(0,\sigma_R)$.

Reference points and performance measures are listed in Tables 12 and 13. The decision tables are designed to present probabilities of undesirable states under alternative 2014 projected catch levels. An undesirable *biomass-based* performance measure occurs when 2015 projected biomass is below the reference point, i.e., $B_{2015}/B_{ReferencePoint} < 1$. Probabilities using biomass-based reference points are only presented for Area 5CD for the reasons given above.

An undesirable *fishing mortality*-based performance measure occurs when projected 2014 fishing mortality is above the reference point, i.e., $F_{2014}/F_{ReferencePoint} > 1$.

Probabilities of undesirable states are measured as the proportion of burned-in posterior samples that meet criteria above (i.e., proportion of posterior samples < 1 for biomass-based performance measures; and proportion of posterior samples > 1 for fishing mortality-based performance measures).

In the previous section, we identified some key sources of uncertainty in this assessment and suggested three solutions to presenting advice incorporating this uncertainty. In both management Areas 5CD and 5AB, we suggested that we cannot further reduce the uncertainty arising from the prior probability distribution for $\ln(M)$ (Figures 32 and 45); the goodness of fit to the mean weight data (Figures 36 and 47); or how well the model should fit to the commercial CPUE data, if at all (Figures 41, 44, 49 and 50).

In the following sections we present the Base Case decision tables for each area, then present alternative "model averaged" decision tables that incorporate the uncertainty from the above sensitivity cases and Base Cases. The model averaging approach is described below. We did not attempt to assign different weights to the alternative models in the construction of the model-averaged results.

BASE CASE MODELS

The decision table for the Area 5CD Base Case model is provided in Table 26. The probability of the 2015 biomass being below the 2014 biomass ranged from 12.4% under no 2014 catch to 64.1% under 2400 t, double the current TAC. The probability of being below the LRP ranged from 12.3% to 24.9% over the range of catch levels considered. The probability of being below the USR was higher and ranged from 51.2% under no 2014 catch to 66.0% over the range of catch levels considered. The probability of the 2014 fishing mortality being greater than the 2013 fishing mortality ranged from 0.0% to 100%. The probability of the 2014 fishing mortality being greater than the LRR ranged from 0.0% to 33.9%. Estimated probabilities at the current TAC 1200 t are shown in bold (Table 26). Under a 2014 catch level of 1200 t, there is an estimated 60% probability that the 2015 biomass will be below the USR and an 18.2% probability that the 2015 biomass will be below the LRP.

The decision table for the Area 5AB Base Case model is provided in Table 27. The range of 2014 catch levels is smaller for Area 5AB, reflecting the apparent smaller stock size and smaller historical catch levels (Table 1). The probability of the 2014 fishing mortality being greater than the 2013 fishing mortality ranged from 0.0% to 100%. The probability of the 2014 fishing mortality being greater than the provisional LRR ranged from 0.0% to 100%, with a 99.5% probability at 850 t. Estimated probabilities under a catch level close to the current TAC of 590 t are shown in bold (Table 27). At the current TAC, the probability of exceeding the provisional LRR is 95.4%. In recent years, the TAC has been under-utilized in Area 5AB (Table 3).

We urge caution in interpreting these results. Lack of survey data for this area implies that estimates of recruitment and biomass have been strongly influenced by the catch and mean weight data for the recent part of the time series, both of which are known to have been influenced by management changes, i.e., the implementation of quotas and changes in the observer program and sampling of length-frequency data.

MODEL AVERAGING

Area 5CD: Hecate Strait

For Area 5CD, we present an alternative decision table with probabilities calculated from combined posterior estimates of performance measures from the following five models:

(i) Base Case;

(ii) the sensitivity case with prior probability distribution for ln(M): N~(0.4,0.2);

(iii) the sensitivity case with $\sigma_W = 0.4$;

(iv) the sensitivity case with $\sigma_O = 0.15$; and

(v) the sensitivity case without commercial CPUE data.

We selected the sensitivity case for the prior on ln(M) that had biomass estimates most divergent from the Base Case model to better bracket the uncertainty due to this parameter. Posterior estimates of biomass relative to the LRP and USR from each scenario are summarized in Figure 53.

The vectors of 1,000 burned-in posterior samples from each of the five models, for each performance measure, under each alternative 2014 catch level, were combined into a single vector of 5,000 samples and probabilities of undesirable states (see above) were calculated from the combined samples.

A similar approach was used in the 2011 assessment of Pacific Hake (Stewart et al. 2011), where two alternative stock assessment models were judged by the Pacific Fishery Management Council's Scientific and Statistical Committee to be equally plausible. Another approach, based on Maximum Posterior Density model results, was used by Stewart et al. (2013) for the 2012 assessment of Pacific Halibut, where the magnitude of natural mortality was considered to be the primary axis of uncertainty. A similar approach is being used for the 2013 assessment of Pacific Halibut, where three alternative, structurally different models, are being used to develop catch advice (Stewart and Martell. 2014). The latter example draws from the ensemble modeling approach commonly used in weather forecasting (e.g., Hamill et al. 2012).

The "Model-Averaged" decision table probabilities for Area 5CD are presented in Table 28. For most performance measures, probabilities were similar to those in the Base Case model. For example, the probability of $B_{2015} < B_{2014}$ under a 2014 TAC of 1200 t was 39.6% for the Base Case model (Table 26), and 42.1% from the averaged models (Table 28). The probability of B_{2015} < LRP under a 2014 catch level of 1200 t was 18.8% for the averaged models, compared with 18.2% for the Base Case model. The probability of B_{2015} < USR under a 2014 catch level of 1200 t was 59.8% for the averaged models, compared with 60.0% for the Base Case model.

Area 5AB: Queen Charlotte Sound

For Area 5AB, we present an alternative decision table with probabilities calculated from combined posterior estimates of performance from the following five models:

(i) Base Case;

(ii) the sensitivity case with prior probability distribution for ln(M): N~(0.4,0.2);

(iii) the sensitivity case with $\sigma_W = 0.4$;

(iv) the sensitivity case with $\sigma_O = 0.15$; and

(v) the sensitivity case using the conditional MPD estimate of σ_j in the objective function.

As for Area 5CD, we selected the sensitivity case for the prior on ln(M) that had biomass estimates most divergent from the Base Case model to better bracket the uncertainty due to this parameter. Posterior estimates of biomass from each scenario are summarized in Figure 54.

The "Model-Averaged" decision table probabilities for Area 5AB are presented in Table 29. The probability of the 2014 fishing mortality being greater than the 2013 fishing mortality ranged from 0.0% to 100%. The probability of the 2014 fishing mortality being greater than the provisional LRR ranged from 0.0% to 99.6%, with a 99.5% probability at 1,550 t. Estimated probabilities under a catch level close to the current TAC of 590 t are shown in bold (Table 27). At the current TAC, the probability of exceeding the provisional LRR is 87.7%. In recent years, the TAC has been under-utilized in Area 5AB (Table 3).

We re-iterate the same cautions in interpreting these results for Area 5AB as for Table 27 (above).

SUMMARY

We presented the alternative, "model averaged" decision tables for Areas 5CD (Table 28) and 5AB (Table 29) in an attempt to more comprehensively incorporate substantial structural uncertainty in the assessments into advice for fishery managers and stakeholders.

However, we emphasize that there are major structural uncertainties that we have not been able to address in this assessment. These include, but are not limited to:

1. The effects of the assumption of constant selectivity in the trawl fishery;
2. The effect of the assumption that recruitment to the fishery, surveys and the spawning biomass is knife-edged at age 2 years;
3. The impact of uncertainty in stock structure in understanding patterns in abundance;
4. The impact of uncertainty in the magnitude of historical discarding and foreign catches;
5. The impact of change in onboard observer coverage and representativeness of length samples from the commercial catch.

Uncertainty is therefore under-represented in this assessment.

RESEARCH NEEDS

There are major structural uncertainties that are not addressed in this assessment. These uncertainties are in part a function of:

1. the lack of age composition data;

2. short fishery-independent indices of abundance with limited trend information;
3. bias in the length frequency data prior to 1996, due to under-representation of lengths of fish that were caught but discarded at sea (Appendix C); and
4. poor understanding of how the relationship between commercial CPUE data and abundance has changed over the course of the fishery.

The latter factor, as is the case for many assessments, is a large contributor to the structural uncertainty of this assessment particularly given the significant changes in management regime, fishing behaviour, and gear efficiencies that are known to have occurred. Changes to management and fishery practices since the 1950s have almost certainly resulted in changes in fishery selectivity throughout the time series, due to changes in mesh size and the spatial distribution of fishing effort.

Members of the fishing industry present at the January 2014 CSAP review of the first draft of this Research Document provided detailed advice about market factors, fishing practices and management changes that have affected patterns of effort directed at Pacific Cod throughout the time series (DFO In prep.[3]). It is recommended that this list of factors be incorporated into a formal document, in collaboration with fishing industry members and fishery managers. This would form a valuable reference for future Pacific Cod assessments and research.

Large changes in management and fishery practices have made interpretation of data for Area 5AB particularly problematic, leading to the rejection of biomass-based reference points using estimated historical biomasses. The estimated average fishing mortality for the period 1956-2004 was accepted provisionally as a LRR for this stock, with the recommendation of regular updates of the assessment to check current estimates of *F*. The committee also proposed using the biennial QCS survey index as a trigger point for new advice. Specifically, the trigger for action would occur when any additional index point (after 2013) falls below 50% of the mean survey indices prior to the new index point. If this occurs, additional analysis will be required and an updated assessment could be requested. Further, a suggestion was made to explore the use of yield-per-recruit type analyses to develop reference points for this stock (e.g., Zhou et al. 2012).

Length-frequency data from the fishery and survey suggest that recruitment to the survey may occur at a younger age than recruitment to the fishery. Therefore the assumption of time-invariant, knife-edged recruitment to the fishery, survey and spawning stock at age 2 years is very likely to be violated for these stocks.

It is unclear whether the Area 5CD and 5AB populations are biologically distinct stocks (Appendix E).Given the relative lack of data for Area 5AB, and lack of strong evidence that the Area 5AB population is distinct from the Area 5CD population, we recommend research into combining the data for the two areas and assessing them as a single stock. We recognize that there are operationally valid reasons for maintaining spatial management, necessary for the functioning of the multi-species integrated groundfish fishery, but highlight the possibility that Pacific Cod in Areas 5AB and 5CD may not be separate biological stocks, which presents challenges to the estimation of stock size and interpretation of biological reference points

We do not believe that many of these uncertainties can be further reduced through application of statistical stock assessment models alone. We recommend development of feedback simulation tools to evaluate the performance of alternative management procedures for Pacific Cod under a range of structural uncertainties, including time-varying selectivity and alternative representations of stock structure (Butterworth and Punt 1999; Smith et al. 1999; Cox and Kronlund 2008). Current, or irresolvable, uncertainties can be specified in an operating model used to generate future observed data that can be used to test the performance of set of candidate management procedures, to provide a relative ranking of their performance relative to specified benchmarks. We define management procedures as the combination of choice of data, stock assessment type, reference points and harvest control rule.

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[3] DFO. In prep. Proceedings of the Pacific regional peer review on the Assessment of British Columbia Pacific Cod for Hecate Strait (Area 5CD) and Queen Charlotte Sound (Area 5AB) in 2013. January 9-10, 2014. DFO Can. Sci. Advis. Sec. Proceed. Ser.

Given the paucity of ageing data available for Pacific Cod, the expense of preparing fin-sections and the uncertainty associated with age readings, we also recommend development of cost-benefit analyses to evaluate the utility of ageing data in decision-making for this stock. Feedback simulation modelling is the only practical means to conduct a cost/benefit analysis of the effects of acquiring ageing data for the assessment and management of Pacific Cod stocks in BC.

The following list of recommendations is provided to help resolve some of the uncertainties noted previously. Work has already commenced on a number of items as indicated by an asterisk:

- Perform analyses to better resolve whether population structure exists within BC waters. A genetic sampling program has been initiated, aimed at addressing questions of stock sub-structure in BC and linkages with stocks outside of BC waters*. Other evidence for differentiation of stocks, e.g., otoliths microchemistry or differences in other biological factors may also be considered
- Analyze existing ageing data to help parameterize a cost-benefit analysis of the utility of age-structured data for this species; and to gain clearer understanding of current proportions at age, precision and potential bias in ageing estimates*.
- Develop updated schedules of maturity-at-age and growth, based on new understanding of age composition and age-at-length (see previous bullet)*.
- Investigate alternative structural hypotheses of drivers of abundance (e.g., Fournier 1983; Walters et al. 1986; Tyler and Crawford 1991), through statistical data analysis and simulation modeling, including feedback simulation*.
- Improve understanding of the magnitude of historical foreign catch and discards, to better characterize uncertainty in these quantities in operating models for feedback simulation.
- Investigate alternative stock assessment models that combine data from Areas 5AB and 5CD.
- Evaluate drivers of spatial changes in fishing effort and management that may improve understanding of the relationship between catch and CPUE data and abundance, and to better characterize uncertainty in historical changes in fishery.
- Improve the methodology used to extract and calculate annual commercial mean weights, as discussed in Appendix C.
- Investigate improvements to the methodology used to calculate the commercial CPUE index, rather than the simple ratio estimator presented in Appendix C.
- Develop feedback simulation tools to evaluate performance of alternative management procedures against background of the considerable uncertainties discussed above*.

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TABLES

*Table 1. Reported catch (mt) of Pacific Cod in **Area 5AB** by Canada and the USA, 1945-2012. The reported discards for the period 1945-1995 are unrepresentative of true discarding because the estimates were taken from logbooks. Discard estimates since 1996 are based on at-sea observations and are considered to be more representative of true discarding.*

5AB			Canada	USA	
Fyear	Discard	Landed	Catch	Landed	Total
1945	0	9	9	-	9
1946	0	23	23	-	23
1947	0	31	31	-	31
1948	0	32	32	-	32
1949	0	46	46	-	46
1950	0	90	90	-	90
1951	0	76	76	-	76
1952	0	103	103	-	103
1953	0	98	98	-	98
1954	0	92	92	-	92
1955	0	59	59	224	283
1956	0	370	370	1341	1711
1957	0	1170	1170	1455	2625
1958	0	481	481	641	1122
1959	0	595	595	342	937
1960	0	385	385	204	589
1961	0	164	164	95	259
1962	0	247	247	145	392
1963	0	161	161	542	703
1964	0	575	575	679	1254
1965	0	687	687	1296	1983
1966	3	696	699	1115	1814
1967	0	461	461	1025	1486
1968	5	403	408	577	985
1969	0	265	265	387	652
1970	0	81	81	197	278
1971	2	230	232	698	930
1972	0	748	748	1667	2415
1973	2	445	447	1417	1864
1974	0	698	698	1539	2237
1975	2	1329	1331	1139	2470
1976	6	1655	1661	610	2271
1977	51	916	967	399	1366
1978	21	1785	1806	156	1962
1979	51	1956	2007	62	2069
1980	22	1259	1281	10	1291
1981	6	811	817	*	817

5AB			Canada	USA	
Fyear	Discard	Landed	Catch	Landed	Total
1982	11	581	592	-	592
1983	0	184	184	-	184
1984	1	395	396	-	396
1985	0	291	291	-	291
1986	9	304	313	-	313
1987	5	3204	3209	-	3209
1988	5	1843	1848	-	1848
1989	6	786	792	-	792
1990	28	842	870	-	870
1991	3	2203	2206	-	2206
1992	0	1863	1863	-	1863
1993	5	1487	1492	-	1492
1994	1	588	589	-	589
1995	2	272	274	-	274
1996	23	199	222	-	222
1997	27	145	172	-	172
1998	27	138	165	-	165
1999	14	113	127	-	127
2000	8	59	67	-	67
2001	8	111	119	-	119
2002	37	183	220	-	220
2003	49	302	351	-	351
2004	70	336	406	-	406
2005	27	320	347	-	347
2006	15	197	212	-	212
2007	6	72	78	-	78
2008	4	31	35	-	35
2009	25	129	154	-	154
2010	19	473	492	-	492
2011	3	362	365	-	365
2012	4	174	178	-	178

Canada:

1945-1953 from pre-1954 table

1954-1995 from GFCatch

* indicates negative USA landed

Table 2. Reported catch (mt) of Pacific Cod in ***Area 5CD*** *by Canada and the USA, 1944-2012. The reported discards for the period 1944-1995 are unrepresentative of true discarding because the estimates were taken from logbooks. Discard estimates since 1996 are based on at-sea observations and are considered to be more representative of true discarding.*

5CD			Canada	USA	
Fyear	Discard	Landed	Catch	Landed	Total
1944	0	2	2	-	2
1945	0	137	137	-	137
1946	0	418	418	-	418
1947	0	38	38	-	38
1948	0	184	184	-	184
1949	0	275	275	-	275
1950	0	426	426	-	426
1951	0	1455	1455	-	1455
1952	0	590	590	-	590
1953	0	426	426	-	426
1954	0	845	845	-	845
1955	0	548	548	*	548
1956	0	1296	1296	722	2018
1957	7	2029	2036	1222	3258
1958	0	2794	2794	2908	5702
1959	0	1883	1883	1632	3515
1960	0	1644	1644	747	2391
1961	7	1365	1372	156	1528
1962	3	1891	1894	165	2059
1963	98	2317	2415	341	2756
1964	86	5994	6080	330	6410
1965	0	8604	8604	266	8870
1966	196	8713	8909	247	9156
1967	344	5572	5916	*	5916
1968	102	3922	4024	29	4053
1969	8	2552	2560	18	2578
1970	1	1186	1187	1	1188
1971	21	1312	1333	*	1333
1972	0	2894	2894	0	2894
1973	11	3813	3824	9	3833
1974	66	5307	5373	*	5373
1975	98	5411	5509	*	5509
1976	46	4141	4187	25	4212
1977	127	3452	3579	9	3588
1978	103	2294	2397	3	2400
1979	231	5505	5736	*	5736
1980	53	4229	4282	*	4282
1981	29	2651	2680	*	2680

5CD Fyear	Discard	Landed	Canada Catch	USA Landed	Total
1982	18	2508	2526	-	2526
1983	68	2294	2362	-	2362
1984	7	1718	1725	-	1725
1985	6	1047	1053	-	1053
1986	103	3715	3818	-	3818
1987	36	9506	9542	-	9542
1988	2	6175	6177	-	6177
1989	36	3426	3462	-	3462
1990	205	3396	3601	-	3601
1991	63	7684	7747	-	7747
1992	35	5223	5258	-	5258
1993	2	3379	3381	-	3381
1994	1	1168	1169	-	1169
1995	1	1020	1021	-	1021
1996	69	1069	1138	-	1138
1997	79	1115	1194	-	1194
1998	33	843	876	-	876
1999	39	577	616	-	616
2000	20	494	514	-	514
2001	31	183	214	-	214
2002	72	199	271	-	271
2003	101	357	458	-	458
2004	60	497	557	-	557
2005	56	683	739	-	739
2006	17	667	684	-	684
2007	8	294	302	-	302
2008	4	274	278	-	278
2009	15	536	551	-	551
2010	30	974	1004	-	1004
2011	4	865	869	-	869
2012	8	693	701	-	701

Canada:
1944-1952 from pre-1954 table
1954-1995 from GFCatch

* indicates negative USA landed

Table 3. Summary of TACs for ***Area 5AB***

Year[a]	Type of quota	TAC	Catch (mt)	Carryover	Comments
2012	IVQ	590	161	-	at Dec 13/12
2011	IVQ	590	367	-	
2010	IVQ	390	476	-	
2009	IVQ	390	121	-	
2008	IVQ	390	30	-	
2007	IVQ	390	72	-	
2006	IVQ	390	197	-	
2005	IVQ	390	320	-	
2004	IVQ	390	336	9	
2003	IVQ	260	302	-	
2002	IVQ	260	183	67	
2001	IVQ	260	111	76	
2000	IVQ	260	59	75	
1999	IVQ	260	113	74	
1998	IVQ	260	138	-	
1997	IVQ	260	145	-	
1996	-	bycatch only	204	-	

[a] Calendar year until 1996. Fishing year April 1 – March 31 starting in 1997; February 21- February 20 starting in 2010

Table 4. Summary of TACs for ***Area 5CDE***

Year[a]	Type of quota	TAC	Catch(mt)	Carryover	Comments
2012	IVQ	1200	661	-	-
2011	IVQ	1200	826	-	-
2010	IVQ	1200	1013	-	-
2009	IVQ	800	510	-	-
2008	IVQ	800	265	-	-
2007	IVQ	800	295	-	-
2006	IVQ	800	668	-	-
2005	IVQ	800	685	-	-
2004	IVQ	400	499	-	-
2003	IVQ	200	362	-	increased to 400 mt in Jan 2004
2002	IVQ	200	200	-	-
2001	IVQ	200	185	-	-
2000	IVQ	1000	495	283	-
1999	IVQ	1000	580	-	-
1998	IVQ	1000	847	-	-
1997	IVQ	1620	1119	-	quota includes 405 mt for Jan-Mar 1997***
1996	bycatch only	bycatch only	1086	-	includes catch for Jan-Mar 1997***
1995	TAC	1870	1329	-	quota 5CD only
1994	TAC	3850	1568	-	5CD only quota
1993	TAC	5100	3825	-	quota 5CD only
1992	TAC	3400	5023	-	quota 5CD only
1991	-	-	7591	-	-
1990	TAC	3800	3495	-	quota 5CD only, provisional until April 1 when an additional 2000 mt may be allocated

[a] Calendar year until 1996. Fishing year April 1 – March 31 starting in 1997; February 21- February 20 starting in 2010

Table 5. Summary of mesh size regulations on the Pacific coast.

Year[a]	Type of restriction	Mesh size (mm)	Carryover	Comments
1993 to 2013	Mandatory restriction	76	minimum mesh size in any part of net, including codend	all areas
1989	Voluntary restriction	127	minimum mesh size of codend	5D only
1990	Voluntary restriction	127	minimum mesh size in last 100 meshes of the net, including codend	5D only, vessels fishing shallower than 80 fms
1991 to 1993	Voluntary restriction	127	minimum mesh size in last 100 meshes of the net, including codend	5D and part of 5C only, fishing in the area bounded on the south by 52° 51'N, on the north by the Canada/US boundary, on the west by 132° 00'W, and on the east by the B.C. coast.
1994	Voluntary restriction	140	minimum mesh size in last 100 meshes of the net, including codend; rest of net is minimum 76	5D and part of 5C only, fishing in the area bounded on the south by 52° 51'N, on the north by the Canada/US boundary, on the west by 132° 00'W, and on the east by the B.C. coast.
1995 to 2013	Mandatory restriction	140	minimum mesh size in last 100 meshes of the net, including codend; rest of net is minimum 76	5D and part of 5C only, fishing in the area bounded on the south by 52° 51'N, on the north by the Canada/US boundary, on the west by 132° 00'W, and on the east by the B.C. coast.

Year[a]	Type of restriction	Mesh size (mm)	Carryover	Comments
2007 to 2011	Voluntary restriction	140	minimum mesh size in last 100 meshes of the net, including codend; rest of net is minimum 76	5AB and part of 5C only, vessels fishing shallower than 60 fm from southern edge of 130-1 to 52°51'N
2011 to 2013	Mandatory restriction	140	minimum mesh size in last 100 meshes of the net, including codend; rest of net is minimum 76	5AB and part of 5C only, vessels fishing shallower than 60 fm from southern edge of 130-1 to 52°51'N
1993 to 1994	Mandatory restriction	108	for synthetic bottom trawls minimum mesh size in last 50 meshes of the net, including codend; rest of net is minimum 76	4B only, areas 13 to 19 and 29
1993 to 1994	Mandatory restriction	120	for manila or sisal bottom trawls minimum mesh size in last 50 meshes of the net, including codend; rest of net is minimum 76	4B only, areas 13 to 19 and 29
1993 to 1994	Mandatory restriction	115	for cotton bottom trawls minimum mesh size in last 50 meshes of the net, including codend; rest of net is minimum 76	4B only, areas 13 to 19 and 29
1995 to 2013	Mandatory restriction	108	minimum mesh size in last 50 meshes of the net, including codend; rest of net is minimum 76	4B only, areas 13 to 19 and 29

[a] Calendar year until 1996. Fishing year April 1 – March 31 starting in 1997; February 21- February 20 starting in 2010

Table 6. Summary of area closures

Year[a]	**Period of closure**	**Details**	**Reason**
2013	Jan 1-Apr 30	Closed to all trawling in those portions of area 101, south of 54° 12’ N latitude and in those waters of areas 102, 104, 105 and subArea 5-20 found south and westerly of a line commencing at 54 ° 10’ N latitude 131° 38 ’30” W longitude thence to 54° 10’ N latitude 131° 5’ W longitude south thence to 53° 30’ N latitude 131° 5’ W longitude thence to 53° 30’ N latitude 130° 28’20”W longitude thence following the eastern boundary of 5-20, 5-22 and 106-1 to 52° 51’N latitude 129° 30’ 37” W longitude thence westerly to 52° 51’N latitude 131° 41’ W longitude thence northerly along the western boundary of subareas 102-2, 102-1 to the point of commencement	5CD only This action is to protect the spawning biomass of Pacific Cod found in Hecate Strait and Dixon Entrance.
2012	Jan 27-Apr 30		
2012	Jan 1-26	Closed to all trawling in area 105, and those portions of area 101, south of 54°12’N latitude and those portions of 102, 104, and Area 4 south of 54°10’N latitude, and Subareas 4-3, 5-10, 5-11, 5-20 to 5-22, 106-1 and that portion of 102-2 north of 52°51’N	5CD only This action is to protect the spawning biomass of Pacific Cod found in Hecate Strait and Dixon Entrance.
2002 to 2011	Jan 1-Apr 30		
2001	Feb 6-Apr 30		
2001	Jan 1-Feb 5	Closed to all trawling in Subareas 102-1, 106-1, that portion of Subarea 102-2 north of 52°51’N, and south of 53°10’N, that portion of Subarea 102-2 north of 53°10’N west of 131°15’W and that portion of Subarea 105-1 west of 131°15’W. The intent of this closure is to reduce the harvesting of Pacific Cod during the spawning period	5CD only This action is to protect the spawning biomass of Pacific Cod found in Hecate Strait and Dixon Entrance.
1996 to 2000 (note: fishery did not open until Feb 16 in 1996)	Jan 1-Apr 15		
1991 to 1992	Jan 1-Mar 31	Closed to all trawling in Subareas 102-1, 106-1, that portion of Subarea 102-2 north of 52°51’N and those portions of Subareas 105-1 and 105-2 westerly of 131°00’W	5CD only This action is to protect the spawning biomass of Pacific Cod found in Hecate Strait and Dixon Entrance.

Year[a]	Period of closure	Details	Reason
1996 to 2012	Jun 1-Jul 15	Closed to bottom trawling in Subareas 2-1, 2-2, 2-3, 102-1 and 104-5; that portion of Subarea 101-7, south of 54°11'N, and east of 132°43'W; those portions of Subareas 101-10 and 104-4, south of 54°15'N; that portion of Subarea 102-2, that is both north of 53°00'N, and west of 131°10'W; that portion of Subarea 104-2, that is both south of 54°15'N, and west of 131°10'W; that portion of Subarea 104-3, that is west of 131°10'W; that portion of Subarea 105-1, that is west of 131°10'W; that portion of Subarea 105-2, west of 131°10'W	5D only The intent of this closure is to protect crabs during the soft-shell period.
1999 to 2013	Jan 1-Mar 31	Closed to both bottom and mid-water trawling in those portions of Subareas 123-3, 123-4, 123-5, 123-6, 124-1 and 124-3 that are found within the area bounded by a line that begins on the Vancouver Island shore near Amphitrite Point lighthouse at 48°55'N latitude 125°32'W longitude; then westerly to 49°04'N latitude 125°44'W longitude; then southerly to 48°55'N latitude 125°50'W longitude; then southerly to 48°47'N latitude 125°46'W longitude; then easterly to 48°44'N latitude 125°32'W longitude; then easterly to 48°49'N latitude 125°17'W longitude; then northerly along the surf line to the point of commencement	3C only The intent of this closure is to reduce the harvesting of Pacific Cod during the spawning period.

a. Calendar year until 1996. Fishing year April 1 – March 31 starting in 1997; February 21- February 20 starting in 2010

Table 7. Criteria used to select length frequency samples of Pacific cod from the GFBio database to estimate the size composition of bottom trawl catches.

1. TRIP_SUB_TYPE = 1 or 4	1=Non-observed domestic 4=Observed domestic
2. SPECIES_CODE = 222	Pacific Cod
3. ACTIVITY_CODE is null	To avoid samples taken during the Hecate Strait Pacific cod monitoring survey
4. GEAR_CODE = 1	Bottom trawl
5. To assign the samples to unsorted, keeper or discard categories must consider both fields	Species_category_code 1 = unsorted, 3 = keepers, 4 = discards Sample_source_code 0 = unknown, 1 = unsorted, 2 = keepers, 3 = discards
SPECIES_CATEGORY_CODE = 1 and SAMPLE_SOURCE_CODE = 1 or Null	Sample source = unsorted
SPECIES_CATEGORY_CODE = 1 and SAMPLE_SOURCE_CODE = 2 OR **SPECIES_CATEGORY_CODE = 3 and SAMPLE_SOURCE_CODE = 2 or Null**	Sample source = keepers
SPECIES_CATEGORY_CODE = 1 and SAMPLE_SOURCE_CODE = 3 OR **SPECIES_CATEGORY_CODE = 4 and SAMPLE_SOURCE_CODE = 3 or Null**	Sample source = discards
6. SAMPLE_TYPE_CODE = 1 or 2 or 6 or 7	1=total catch 2=random 6=random from randomly assigned set 7=random from set after randomly assigned set
7. SAMPLE_ID <> 173726, 173740, 191471,184243, 184159, 215903, 223726	These samples were coded as being from Pacific cod but have a size composition inconsistent with the species. These samples were therefore excluded from further analysis.
8. FISHING YEAR	April 1 – March 31. Based on end of fishing event (fe_begin_retrieval_time)
9. QUARTER	Based on end of fishing event (fe_begin_retrieval_time)

Table 8. List of parameters for the delay difference model. Estimated (or fixed) leading parameters are highlighted in bold type. See Tables 12-14 for derivation of other parameters.

Parameter	Description	Value
Indices		
t	Time (years).	1956-2013
j	Gear (fishery or index of abundance)	
a	Age (years) used for initializing numbers in first year.	2-10 y
A	Maximum age (years) used for initializing numbers in first year.	10 y
Fixed input parameters		
k	Age at knife-edge recruitment	2 y
L_∞	Theoretical maximum length	89.48 cm
K_{VB}	von Bertalanffy growth rate	0.307
aLW	Scaling parameter of the length weight relationship	7.38e-6
bLW	Exponent of the length weight relationship	3.0963
t_0	Theoretical age at 0 cm	-0.116
α_g	Intercept of the Ford-Walford plot, for all ages > k	1.4054
ρ_g	Slope of the Ford-Walford plot, for all ages > k	0.8376
W_k	Weight at age of recruitment k	0.8278 kg
Annual input data		
C_t	Catch (metric tonnes)	
W_t	Mean weight of individuals in population (kg)	
$I_{j,t}$	Index of abundance j (Survey or commercial trawl CPUE)	
$CV_{j,t}$	Annual coefficients of variation in index of abundance observations	
Time-invariant parameters		
$\mathbf{R_0}$	**Equilibrium unfished age 0 recruits**[a]	
$\mathbf{h}$	**Steepness of the stock-recruit relationship**	
$\mathbf{M}$	**Natural mortality**[a]	
$\mathbf{R_{Avg}}$	**Average annual recruitment**[a]	
$\mathbf{R_{Avg\_init}}$	**Average annual recruitment for initializing the model**[a]	
CR	Recruitment compensation ratio	
a	Slope of the stock-recruit function at the origin	
b	Scaling parameter of stock-recruit function	
N_0	Equilibrium unfished numbers	
B_0	Equilibrium unfished biomass	
S_0	Equilibrium unfished survival rate	
$\overline{W}_0$	Equilibrium unfished mean weight	
c_j	Additional process error in index of abundance observations for gear j	

Parameter	Description
Time-varying parameters	
$\boldsymbol{\omega_t}$	**Ln-recruitment deviations**[a]
$\boldsymbol{F_t}$	**Fishing mortality in the trawl fishery**[a]
S_t	Annual survival rate
N_t	Numbers
R_t	Recruits
B_t	Biomass
$\bar{W}_t$	Predicted mean weight
Likelihood components	
σ_R	Standard deviation in ln recruitment residuals
σ_O	Overall standard deviation in observation residuals
σ_{ij}	Annual standard deviation in observation residuals for each survey
σ_C	Standard deviation in catch
σ_W	Standard deviation in mean weight
$\boldsymbol{\varphi^{-2}}$	**Inverse of the total variance (total precision)**
$\boldsymbol{\rho}$	**Proportion of total variance due to observation error**
$\boldsymbol{\tau_j}$	**Variance in age composition residuals**[b]
$\boldsymbol{q_j}$	**Constant of proportionality in indices of (catchability)** [a,b]
$d_{j,t}^2$	Residual ln difference for *j* indices of abundance
d_{Ct}^2	Residual ln difference for catch data
d_{Wt}^2	Residual ln difference for mean weight data
Fishery reference points	
MSY	Maximum sustainable yield
F_{MSY}	Long-term fixed fishing mortality that produces MSY
B_{MSY}	Long-term fixed spawning biomass at MSY
$F_{Avg[t1\text{-}t2]}$	Average estimated fishing mortality rate between t_1 and t_2
$B_{Avg[t1\text{-}t2]}$	Average estimated spawning biomass between t_1 and t_2

a. Estimated in log space
b. Conditional MPD estimates

Table 9. Summary of equilibrium equations for the delay difference model.

	Equilibrium equations for calculation of stock-recruit parameters
T9.1	**Equilibrium unfished survival** $S_0 = e^{-M}$
T9.2	**Equilibrium unfished mean weight** $\overline{w}_0 = \dfrac{S_0 \alpha_g + w_k (1 - S_0)}{1 - \rho_g S_0}$
T9.3	**Equilibrium unfished numbers** $N_0 = \dfrac{R_0}{(1 - S_0)}$
T9.4	**Equilibrium unfished biomass** $B_0 = N_0 \overline{w}_0$
T9.5	**Recruitment compensation ratio (Beverton-Holt)** $\mathrm{CR} = \dfrac{4h}{1-h}$
T9.6	**Parameters of the stock-recruit relationship (Beverton-Holt)** $b = \dfrac{\mathrm{CR} - 1}{B_0}$
	Equilibrium equations for fishery reference points
T9.7	**Equilibrium survival rate at fixed long-term fishing mortality *F*ₑ** $S_e = e^{-(M+F_e)}$
T9.8	**Equilibrium long-term mean weight at *F*ₑ** $\overline{w}_e = \dfrac{S_e \alpha_g + w_k (1 - S_e)}{1 - \rho_g S_e}$
T9.9	**Equilibrium long-term biomass at *F*ₑ** $B_e = -\dfrac{\left(-\overline{\mathrm{W}}_e + \mathrm{S}_e \alpha_g + \mathrm{S}_e \rho_g \overline{\mathrm{W}}_e + W_k a \overline{\mathrm{W}}_e\right)}{b\left(-\overline{\mathrm{W}}_e + \mathrm{S}_e \alpha_g + \mathrm{S}_e \rho_g \overline{\mathrm{W}}_e\right)}$
T9.10	**Equilibrium long-term yield at *F*ₑ** $Y_e = B_e \dfrac{F_e}{(F_e + M)} \left(1 - e^{-(F_e+M)}\right)$

Table 10. Time-dynamic equations and likelihood components for the delay difference model.

	Time-dynamic equations
T10.1	**Survival rate** $S_t = e^{-(M+F_t)}$
T10.2	**Initial numbers at age calculations** $\left\{ \begin{array}{ll} N_{2,1} = R_{Avg} e^{\omega_1} & a = 2 \\ N_{a,1} = \left(R_{AvgInit} e^{\omega Init_a} \right) e^{-M(a-2)} & 2 < a < A \\ N_{A,1} = \dfrac{\left(R_{AvgInit} e^{\omega Init_A} \right) e^{-M(A-2)}}{\left(1 - e^{-M}\right)} & a = A \end{array} \right\}$
T10.3	**Numbers** $\left\{ \begin{array}{ll} N_t = \sum_{t=2}^{A} N_{a,1} & t = 1956 \\ N_t = S_{t-1} N_{t-1} + R_t & t > 1956 \end{array} \right\}$
T10.4	**Biomass** $\left\{ \begin{array}{ll} B_t = \sum_{a=2}^{A} N_{a,t} w_{a,t} & t = 1956 \\ B_t = S_{t-1} \left(\alpha_g N_{t-1} + \rho_g B_{t-1} \right) + W_k R_t & t > 1956 \end{array} \right\}$
T10.5	**Recruits** $R_t = R_{Avg} e^{\omega_t - \frac{\sigma_R^2}{2}}$
	Predicted variables used in objective function
T10.6	**Predicted catch** $\hat{C}_t = B_t \dfrac{F_t}{(F_t + M)} \left(1 - e^{-(F_t + M)}\right)$
T10.7	**Predicted mean weight** $\hat{\bar{W}}_t = \dfrac{B_t}{N_t}$
T10.8	**Predicted recruits** $\hat{R}_t = \dfrac{aB_{t-k+1}}{1 + bB_{t-k+1}}$

Table 11. Calculation of variance parameters, residuals and likelihoods.

	Variance parameters
	Base standard deviation in index of abundance residuals
T11.1	$\sigma_O = \sqrt{\frac{\rho}{\varphi^{-2}}}$
	Standard deviation in ln recruitment residuals
T11.2	$\sigma_R = \sqrt{\frac{(1-\rho)}{\varphi^{-2}}}$
	Standard deviation in index of abundance observations
T11.3	$\sigma_{jt} = \frac{\sigma_O}{c_{j,t}}$
	Weighting term for index observations
T11.4	$c_{j,t} = \frac{1}{\mathrm{CV}_{j,t}}$
	Indices of abundance
	Residuals
T11.5	$z_{j,t} = \ln\left(I_{j,t}\right) - \ln\left(\hat{B}_t\right)$
T11.6	$\overline{z}_j = \frac{\sum_t^{n_j} z_{j,t}}{n_j}$
T11.7	$d_{j,t} = z_{j,t} - \overline{z}_j$
	Ln likelihood
T11.8	$L_{j,t} = \ln\left(\sigma_{j,t}^2\right) + \frac{d_{jt}^2}{2\sigma_{j,t}^2}$
	Catch **Residuals**
T11.9	$d_{Ct} = \ln\left(C_t\right) - \ln\left(\hat{C}_t\right)$
	Ln likelihood
T11.10	$L_t = \ln\left({\sigma_C}^2\right) + \frac{{d_{Ct}}^2}{2{\sigma_C}^2}$

	Mean weight
	Residuals
T11.11	$d_{W\,t} = \ln\left(\bar{W}_t\right) - \ln\left(\hat{\bar{W}}_t\right)$
	Ln likelihood
T11.12	$l_t = \ln\left(\sigma_W{}^2\right) + \frac{d_{W\,t}{}^2}{2\sigma_W{}^2}$
	Recruitment
	Residuals
T11.13	$d_{Rt} = \ln\left(R_t\right) - \ln\left(\hat{R}_t\right)$
	Ln likelihood
T11.14	$l_t = \ln\left(\sigma_R{}^2\right) + \frac{d_{Rt}^2}{2\sigma_R{}^2}$

Table 12. List of reference points. Reference points listed under "Other reference points" were calculated but are not used in decision tables. They are presented for comparison with historical reference points. No biomass-based reference points were accepted for Area 5AB (see text).

Reference Point	**Definition**	**Role in Harvest Control Rule**
Benchmarks		
F_{2013}	Estimated 2013 fishing mortality rate	None but used as bench-mark
B_{2014}	Estimated 2014 biomass	None but used as bench-mark
Historical reference points		
$F_{Avg[1956\text{-}2004]}$	Average estimated fishing mortality for the period 1956-2004	Limit Removal Rate (LRR)
B_{Min}	Estimated biomass in 1971	Limit Reference Point (LRP) (Area 5CD only)
$B_{Avg[1956\text{-}2004]}$	Average estimated biomass for the period 1956-2004	Upper Stock Reference (USR) (Area 5CD only)
Other reference points (not used)		
F_{MSY}	Long-term fishing mortality that produces Maximum Sustainable Yield	Limit Removal Rate (LRR)
$0.8B_{MSY}$	80% of long-term biomass at MSY	Upper Stock Reference (USR)
$0.4B_{MSY}$	40% of long-term biomass at MSY	Lower Reference Point (LRP)
$F_{Avg[1956\text{-}2012]}$	Average estimated fishing mortality for the period 1956-2012	Limit Removal Rate (LRR)
$B_{Avg[1956\text{-}2012]}$	Average estimated biomass for the period 1956-2012	Upper Stock Reference (USR)

Table 13. List of Performance Measures for use in this assessment. No biomass-based performance measures were accepted for Area 5AB (see text).

Performance Measure	Role in Harvest Control Rule
Benchmarks	
F_{2014}/F_{2013}	None but measures whether fishing mortality is projected to increase or decrease under each projected catch level
B_{2015}/B_{2014}	None but measures whether biomass is projected to increase or decrease under each projected catch level (Area 5CD only)
Historical reference points	
$F_{2014}/F_{Avg[1956\text{-}2004]}$	Measures whether fishing mortality is projected to exceed LRR under each projected catch level
B_{2015}/B_{Min}	Measures whether biomass is projected to be below LRP under each projected catch level (Area 5CD only)
$B_{2015}/B_{Avg[1956\text{-}2004]}$	Measures whether biomass is projected to be below USR under each projected catch level (Area 5CD only)

Table 14. Annual indices of abundance from the Hecate Strait Assemblage Survey and Hecate Strait Synoptic Survey and annual CVs

Assemblage	Index	$CV_{j,t}$
1984	1142.4	0.3031
1987	3875.7	0.3498
1989	4102.8	0.4254
1991	1031.8	0.2977
1993	1255.6	0.2396
1995	1419.8	0.4609
1996	1159.6	0.3739
1998	4253.0	0.5095
2000	436.1	0.1991
2002	2025.9	0.2704
2003	1288.7	0.2088
Synoptic	**Index**	$CV_{j,t}$
2003	1940.7	0.2341
2005	585.5	0.2076
2007	2497.6	0.4416
2011	1873.8	0.2607
2013	2351.2	0.2432

Table 15. Fixed parameters and prior probability distributions used in the Base Case models. Subscripts on Ln(q) parameters indicate: A = Hecate Strait Multispecies Assemblage Survey; S = Hecate Strait Synoptic Survey; and CPUE = commercial CPUE data for the years 1956-1995. σ_R *and* σ_O *were derived from* φ^{-2} *and* ρ *using Eq. T11.1 and T11.2.*

Parameter	**5CD Base Case**	**5AB Base Case**
Ln(R_0)	*Uniform*(1,15)	*Uniform*(1,15)
Ln(R_{Avg})	*Uniform*(1,12)	*Uniform*(1,12)
Ln(R_{Avg_init})	*Uniform*(1,12)	*Uniform*(1,12)
Steepness, h	*Beta*(5.833, 2.5)	*Beta*(5.833, 2.5)
Ln(M)	*Norm*(-0.693, 0.1)	*Norm*(-0.693, 0.1)
Ln(q_A)	*Norm*(0,0.5)	*NA*
Ln(q_S)	*Norm*(0, 0.5)	*Norm*(0, 0.5)
Ln(q_{CPUE})	*Uniform*(-16, 0)	*Uniform*(-16, 0)
σ_C	0.05	0.05
σ_W	0.2	0.2
Variance parameters		
φ^{-2}	1.423488	1.423488
ρ	0.088968	0.088968
σ_R	0.8	0.8
σ_O	0.25	0.25

Table 16. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters from the ***Area 5CD*** *Base Case model. Subscripts on q parameters indicate: A = Hecate Strait Multispecies Assemblage Survey; S = Hecate Strait Synoptic Survey; and CPUE = commercial CPUE data for the years 1956-1995. B_0 was derived from leading parameters using Eq. T9.4.*

Parameter	2.5%	50%	97.5%	MPD
R_0	2.501	4.065	12.544	4.857
Steepness (h)	0.404	0.657	0.905	0.663
M	0.339	0.393	0.454	0.393
R_{Avg}	1.330	2.401	4.336	2.760
R_{Avg_init}	0.037	0.473	3.057	1.812
q_A	0.105	0.140	0.181	0.145
q_S	0.087	0.141	0.228	0.146
q_{CPUE}	0.014	0.019	0.024	0.020
B_0	22.350	35.105	107.054	41.949

*Table 17. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of biomass (thousands of tonnes) from the **Area 5CD** Base Case model.*

Fishing year	2.50%	50%	97.50%	MPD
1956	10.618	16.545	25.516	16.089
1957	14.726	20.515	29.735	19.761
1958	16.491	22.777	31.914	21.867
1959	13.811	19.225	27.153	18.575
1960	12.142	17.184	24.603	16.549
1961	11.194	16.238	23.950	15.760
1962	12.725	18.859	28.647	18.448
1963	18.906	28.934	42.446	27.503
1964	31.496	42.295	58.220	41.185
1965	32.791	43.382	57.757	42.150
1966	27.294	35.492	47.769	34.263
1967	19.677	25.699	35.555	24.767
1968	13.826	18.910	27.416	18.193
1969	10.094	14.331	21.103	13.768
1970	7.901	11.770	17.785	11.223
1971	8.026	12.198	18.675	11.618
1972	17.834	24.894	35.554	24.231
1973	23.262	32.238	45.331	30.978
1974	24.455	32.541	45.353	31.383
1975	20.783	27.906	39.376	26.841
1976	15.888	22.256	32.075	21.457
1977	15.010	20.669	29.222	19.812
1978	13.395	19.018	27.360	18.261
1979	16.275	21.809	29.547	20.988
1980	13.978	19.804	27.704	18.860
1981	13.228	18.462	26.074	17.689
1982	12.860	17.942	25.284	17.274
1983	11.956	16.159	22.891	15.606
1984	10.637	14.509	21.386	14.158
1985	9.612	13.984	21.419	13.672
1986	17.918	27.254	39.606	25.825
1987	29.165	37.657	50.368	36.395
1988	23.848	31.442	43.361	30.414
1989	18.283	25.179	35.310	24.149
1990	16.939	23.141	31.062	22.310
1991	17.543	22.638	28.936	22.097
1992	12.816	16.415	21.527	15.975
1993	8.832	11.578	15.853	11.210
1994	5.946	8.278	11.890	7.966
1995	5.556	7.663	11.009	7.376
1996	5.140	7.240	10.254	6.959
1997	4.459	6.543	9.742	6.216
1998	3.658	5.706	8.795	5.372
1999	3.430	5.287	8.542	5.037
2000	3.096	4.997	8.067	4.752
2001	2.635	4.589	7.589	4.337
2002	5.216	7.930	11.857	7.500
2003	7.048	10.712	15.969	10.200
2004	7.132	11.230	16.884	10.712
2005	6.472	10.447	16.163	9.982
2006	5.525	9.190	14.436	8.761
2007	4.705	8.262	13.775	7.917
2008	5.891	10.197	18.008	9.830
2009	7.392	12.630	22.536	12.249
2010	8.246	14.071	23.935	13.580
2011	7.793	13.685	23.878	13.181
2012	7.093	13.354	23.223	12.662
2013	8.271	14.907	26.828	14.597
2014	8.819	16.181	31.828	16.802

Table 18. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of recruits (million) from the ***Area 5CD*** *Base Case model.*

Fishing year	2.50%	50%	97.50%	MPD
1958	0.718	4.224	11.548	4.655
1959	0.573	3.026	8.379	3.371
1960	0.511	2.551	6.231	2.618
1961	0.532	2.718	6.889	2.992
1962	1.307	5.490	14.028	5.744
1963	2.072	12.735	28.083	12.493
1964	1.984	13.478	29.353	14.792
1965	0.517	3.779	13.763	4.096
1966	0.708	3.796	10.695	4.215
1967	0.571	3.283	7.642	3.519
1968	0.460	1.826	4.799	1.995
1969	0.408	1.812	4.633	1.927
1970	0.348	1.562	3.873	1.627
1971	0.748	2.941	7.465	2.981
1972	8.166	17.088	27.534	16.940
1973	0.438	3.334	11.737	3.428
1974	0.841	4.743	11.826	5.159
1975	0.450	2.579	7.671	2.806
1976	0.741	3.135	7.719	3.289
1977	1.589	5.248	10.057	5.298
1978	0.499	2.434	6.990	2.784
1979	1.947	7.384	14.093	7.218
1980	0.793	3.810	9.264	4.058
1981	0.941	3.933	8.691	4.133
1982	0.466	2.504	6.295	2.762
1983	0.371	1.878	5.203	1.939
1984	0.568	2.473	5.673	2.596
1985	0.451	2.158	6.413	2.382
1986	6.241	17.734	30.586	16.642
1987	0.883	9.271	22.481	10.374
1988	0.360	2.384	8.229	2.664
1989	0.421	2.257	6.540	2.465
1990	1.066	4.587	9.709	4.810
1991	0.933	4.967	10.539	5.333
1992	0.544	3.013	7.108	3.187
1993	0.325	1.630	4.019	1.667
1994	0.240	1.118	2.685	1.207
1995	0.347	1.287	3.146	1.341
1996	0.267	1.133	2.960	1.174
1997	0.239	0.953	2.373	0.973
1998	0.251	0.930	2.284	0.946
1999	0.292	0.995	2.091	1.030
2000	0.131	0.549	1.524	0.587
2001	0.105	0.490	1.417	0.525
2002	2.388	4.678	7.971	4.508
2003	0.205	1.224	4.037	1.337
2004	0.220	0.932	2.843	1.013
2005	0.160	0.701	2.016	0.734
2006	0.223	0.785	2.155	0.861
2007	0.291	1.016	2.797	1.100
2008	1.140	3.561	9.121	3.551
2009	0.371	2.135	6.094	2.313
2010	0.312	1.911	6.295	2.152
2011	0.247	1.217	3.843	1.324
2012	0.338	1.635	5.236	1.787
2013	0.420	3.294	13.640	4.358

Table 19 Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of fishing mortality (y^{-1}) from the ***Area 5CD*** *Base Case model.*

Fishing Year	2.50%	50%	97.50%	MPD
1956	0.100	0.156	0.259	0.163
1957	0.143	0.210	0.313	0.219
1958	0.244	0.356	0.516	0.372
1959	0.171	0.246	0.353	0.258
1960	0.124	0.182	0.268	0.191
1961	0.081	0.119	0.177	0.124
1962	0.091	0.140	0.213	0.144
1963	0.081	0.121	0.195	0.128
1964	0.143	0.201	0.284	0.206
1965	0.204	0.281	0.385	0.290
1966	0.263	0.369	0.505	0.385
1967	0.226	0.324	0.447	0.338
1968	0.200	0.299	0.428	0.311
1969	0.157	0.243	0.370	0.255
1970	0.084	0.130	0.199	0.136
1971	0.091	0.140	0.227	0.148
1972	0.104	0.150	0.215	0.155
1973	0.106	0.155	0.220	0.161
1974	0.156	0.224	0.305	0.231
1975	0.186	0.272	0.387	0.284
1976	0.173	0.259	0.376	0.269
1977	0.160	0.234	0.340	0.245
1978	0.112	0.164	0.245	0.172
1979	0.263	0.374	0.542	0.394
1980	0.209	0.299	0.452	0.317
1981	0.130	0.191	0.284	0.200
1982	0.131	0.186	0.262	0.193
1983	0.132	0.193	0.273	0.201
1984	0.103	0.153	0.221	0.158
1985	0.061	0.095	0.142	0.097
1986	0.125	0.184	0.300	0.195
1987	0.256	0.359	0.493	0.376
1988	0.193	0.267	0.374	0.280
1989	0.126	0.182	0.258	0.189
1990	0.151	0.206	0.298	0.215
1991	0.385	0.513	0.717	0.529
1992	0.345	0.480	0.658	0.493
1993	0.297	0.425	0.582	0.442
1994	0.123	0.187	0.268	0.193
1995	0.118	0.174	0.240	0.180
1996	0.144	0.210	0.305	0.220
1997	0.160	0.248	0.386	0.261
1998	0.130	0.205	0.338	0.219
1999	0.094	0.153	0.249	0.160
2000	0.081	0.134	0.220	0.139
2001	0.035	0.058	0.103	0.061
2002	0.028	0.043	0.065	0.045
2003	0.035	0.053	0.082	0.056
2004	0.041	0.062	0.098	0.065
2005	0.057	0.089	0.149	0.094
2006	0.059	0.095	0.163	0.099
2007	0.027	0.045	0.080	0.047
2008	0.019	0.034	0.059	0.035
2009	0.030	0.053	0.093	0.056
2010	0.052	0.090	0.159	0.093
2011	0.044	0.080	0.149	0.083
2012	0.036	0.066	0.128	0.069
2013	0.029	0.052	0.096	0.053

Table 20. Reference points calculated in the ***Area 5CD*** *Base Case model with quantiles showing the 95% posterior credibility interval. Only reference points shown in bold type are used in decision tables in this assessment. LRP = Lower Reference Point; USR = Upper Stock Reference; LRR = Limit Removal Rate. All biomass units are thousands of tonnes. Reference points listed under "Other reference points" were calculated but are not used in decision tables. They are presented for comparison with proposed historical reference points. See also Figure 19.*

Reference point	**2.50%**	**25%**	**50%**	**75%**	**97.50%**
F_{2013}	0.029	0.042	0.052	0.065	0.097
B_{2014}	8.478	13.254	16.701	21.189	33.263
B_{1971} (LRP)	7.902	10.556	12.182	14.143	18.659
$F_{Avg[1956-2004]}$ (LRR)	0.165	0.200	0.220	0.239	0.275
$B_{Avg[1956-2004]}$ (USR)	15.685	17.752	19.258	21.051	25.567
Other reference points (not used)					
F_{MSY}	0.148	0.246	0.312	0.386	0.527
B_{MSY}	7.301	10.012	12.185	15.386	38.396
$F_{Avg[1956-2012]}$	0.150	0.182	0.199	0.217	0.250
$B_{Avg[1956-2012]}$	14.772	16.802	18.217	19.864	23.962

*Table 21. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of key parameters from the **Area 5AB** Base Case model . Subscripts on q parameters indicate: S = Queen Charlotte Sound Synoptic Survey; and CPUE = commercial CPUE data for the years 1956-1995. B_0 was derived from leading parameters using Eq. T9.4.*

Parameter	**2.5%**	**50%**	**97.5%**	**MPD**
R_0	0.577	0.958	2.138	1.226
Steepness (*h*)	0.385	0.586	0.840	0.580
M	0.366	0.437	0.516	0.426
R_{Avg}	0.273	0.504	0.936	0.572
R_{Avg_init}	0.016	0.174	1.769	0.909
q_S	0.338	0.831	1.285	0.925
q_{CPUE}	0.015	0.020	0.025	0.021
B_0	4.417	7.046	15.248	9.416

*Table 22. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of biomass (thousand tonnes) from the **Area 5AB** Base Case model.*

Fishing year	2.50%	50%	97.50%	MPD
1956	5.725	9.152	13.510	8.080
1957	7.290	9.526	13.151	8.753
1958	5.197	7.241	10.515	6.650
1959	4.388	6.053	8.714	5.598
1960	3.345	4.714	6.723	4.365
1961	2.576	3.668	5.208	3.406
1962	2.141	3.031	4.344	2.844
1963	1.803	2.825	4.471	2.633
1964	6.445	8.584	12.006	8.072
1965	8.006	10.761	15.173	10.109
1966	6.702	8.903	12.407	8.305
1967	4.886	6.442	9.054	6.027
1968	3.262	4.456	6.440	4.186
1969	2.195	3.231	4.903	3.063
1970	1.886	3.023	5.004	2.972
1971	2.657	6.109	9.406	3.402
1972	4.709	8.465	13.716	9.952
1973	8.133	11.579	16.848	11.531
1974	8.714	12.791	18.784	11.473
1975	9.343	12.943	19.079	11.909
1976	8.339	11.765	17.583	10.764
1977	7.397	10.448	15.344	9.599
1978	7.551	10.224	14.665	9.466
1979	6.510	8.687	12.633	8.036
1980	4.633	6.403	9.251	5.825
1981	3.324	4.678	6.947	4.260
1982	2.402	3.562	5.350	3.239
1983	1.844	2.740	4.255	2.510
1984	1.896	2.712	3.947	2.495
1985	1.553	2.332	3.442	2.152
1986	1.586	2.435	4.097	2.278
1987	6.953	8.703	11.605	8.231
1988	5.262	7.440	10.979	6.836
1989	3.860	5.847	8.941	5.317
1990	3.496	5.465	8.218	4.987
1991	5.491	6.803	8.850	6.464
1992	4.191	5.315	7.068	4.988
1993	2.946	3.588	4.860	3.384
1994	1.436	1.885	2.846	1.758
1995	0.865	1.192	1.943	1.106
1996	0.647	0.929	1.550	0.863
1997	0.497	0.727	1.336	0.679
1998	0.392	0.607	1.217	0.562
1999	0.232	0.443	1.045	0.406
2000	0.097	0.298	0.869	0.267
2001	0.559	0.966	2.199	0.875
2002	0.841	1.335	2.910	1.211
2003	0.794	1.304	2.959	1.184
2004	0.979	1.360	2.896	1.252
2005	0.775	1.096	2.441	1.005
2006	0.462	0.731	1.788	0.651
2007	0.248	0.511	1.496	0.437
2008	0.407	0.844	2.327	0.716
2009	0.659	1.229	2.990	1.072
2010	1.130	1.695	3.888	1.527
2011	0.833	1.459	3.776	1.271
2012	0.472	1.151	3.317	0.956
2013	0.674	1.223	3.047	1.082
2014	0.744	1.389	3.314	1.339

Table 23. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of recruits (millions) from the ***Area 5AB*** *Base Case model.*

Fishing year	2.50%	50%	97.50%	MPD
1958	0.108	0.686	2.271	0.657
1959	0.131	0.729	1.935	0.776
1960	0.070	0.336	0.928	0.346
1961	0.066	0.285	0.788	0.302
1962	0.065	0.253	0.740	0.258
1963	0.231	0.750	2.257	0.760
1964	5.220	8.065	11.961	7.619
1965	0.071	0.494	2.234	0.524
1966	0.119	0.749	2.281	0.837
1967	0.107	0.557	1.497	0.596
1968	0.142	0.545	1.381	0.585
1969	0.106	0.435	1.186	0.478
1970	0.271	0.984	2.523	1.091
1971	0.183	3.985	8.259	0.720
1972	0.049	0.314	13.010	9.253
1973	0.229	6.527	12.988	1.434
1974	0.137	1.313	7.748	2.336
1975	0.287	3.322	8.443	3.920
1976	0.204	1.756	6.027	1.567
1977	0.207	2.168	5.914	2.312
1978	0.243	1.906	5.495	1.912
1979	0.179	1.318	3.298	1.345
1980	0.120	0.683	1.913	0.710
1981	0.119	0.452	1.251	0.489
1982	0.100	0.419	1.025	0.420
1983	0.074	0.336	0.817	0.331
1984	0.150	0.550	1.161	0.551
1985	0.060	0.272	0.797	0.275
1986	0.253	0.810	2.041	0.767
1987	5.601	7.897	11.285	7.548
1988	0.076	0.496	2.123	0.540
1989	0.127	0.790	2.136	0.871
1990	0.214	0.970	2.548	1.010
1991	1.413	3.282	5.249	3.225
1992	0.111	0.601	1.896	0.631
1993	0.201	0.797	1.671	0.858
1994	0.046	0.187	0.472	0.195
1995	0.053	0.173	0.419	0.177
1996	0.051	0.178	0.427	0.179
1997	0.039	0.139	0.369	0.132
1998	0.041	0.134	0.346	0.133
1999	0.014	0.056	0.161	0.057
2000	0.010	0.038	0.127	0.038
2001	0.548	0.915	1.923	0.852
2002	0.022	0.148	0.530	0.147
2003	0.060	0.256	0.781	0.256
2004	0.265	0.625	1.050	0.595
2005	0.035	0.141	0.381	0.144
2006	0.030	0.094	0.266	0.093
2007	0.027	0.086	0.252	0.084
2008	0.255	0.552	1.361	0.473
2009	0.048	0.249	0.718	0.255
2010	0.322	0.776	1.530	0.706
2011	0.048	0.214	0.674	0.217
2012	0.035	0.159	0.507	0.150
2013	0.069	0.408	1.156	0.459

Table 24. Posterior (2.5th percentile, Median, and 97.5th percentile) and MPD estimates of fishing mortality (y^{-1}) from the ***Area 5AB*** *Base Case model.*

Fishing year	2.50%	50%	97.50%	MPD
1956	0.171	0.258	0.443	0.296
1957	0.292	0.405	0.561	0.448
1958	0.144	0.209	0.298	0.229
1959	0.144	0.211	0.295	0.228
1960	0.115	0.166	0.238	0.180
1961	0.062	0.091	0.130	0.098
1962	0.116	0.173	0.257	0.184
1963	0.212	0.360	0.643	0.388
1964	0.139	0.197	0.267	0.209
1965	0.179	0.255	0.359	0.272
1966	0.201	0.289	0.398	0.309
1967	0.230	0.330	0.463	0.355
1968	0.209	0.316	0.458	0.337
1969	0.181	0.284	0.441	0.299
1970	0.073	0.120	0.202	0.121
1971	0.129	0.206	0.556	0.399
1972	0.251	0.419	0.913	0.346
1973	0.148	0.221	0.324	0.218
1974	0.157	0.238	0.370	0.269
1975	0.174	0.264	0.389	0.289
1976	0.180	0.269	0.407	0.296
1977	0.118	0.174	0.251	0.190
1978	0.179	0.265	0.375	0.290
1979	0.231	0.345	0.481	0.375
1980	0.188	0.287	0.408	0.316
1981	0.160	0.243	0.356	0.268
1982	0.147	0.231	0.352	0.254
1983	0.055	0.086	0.131	0.094
1984	0.129	0.196	0.293	0.215
1985	0.109	0.167	0.261	0.181
1986	0.100	0.169	0.276	0.183
1987	0.419	0.589	0.798	0.635
1988	0.234	0.362	0.542	0.399
1989	0.119	0.183	0.280	0.201
1990	0.145	0.215	0.357	0.238
1991	0.362	0.493	0.658	0.528
1992	0.394	0.555	0.749	0.598
1993	0.475	0.701	0.928	0.758
1994	0.303	0.483	0.672	0.522
1995	0.192	0.331	0.477	0.357
1996	0.197	0.342	0.527	0.374
1997	0.174	0.341	0.545	0.367
1998	0.184	0.403	0.694	0.439
1999	0.158	0.434	1.005	0.476
2000	0.102	0.323	1.596	0.364
2001	0.073	0.163	0.293	0.182
2002	0.101	0.224	0.381	0.250
2003	0.162	0.393	0.733	0.441
2004	0.184	0.449	0.679	0.497
2005	0.191	0.493	0.754	0.544
2006	0.152	0.430	0.807	0.503
2007	0.062	0.209	0.479	0.246
2008	0.019	0.053	0.111	0.062
2009	0.067	0.168	0.332	0.192
2010	0.172	0.430	0.718	0.491
2011	0.130	0.363	0.754	0.426
2012	0.069	0.212	0.605	0.257
2013	0.105	0.290	0.613	0.334

*Table 25. Reference points calculated with the **5AB Base Case** model with quantiles showing the 95% posterior credibility interval. Only reference points shown in bold type are used in decision tables in this assessment. LRR = Limit Removal Rate. Reference points listed under "Other reference points" were calculated but are not used in decision tables. They are presented for comparison with proposed historical reference points. See also Figure 30.*

Reference point	**2.50%**	**25%**	**50%**	**75%**	**97.50%**
F_{2013}	0.111	0.226	0.289	0.373	0.616
$F_{Avg[1956-2004]}$ (LRR)	0.210	0.272	0.305	0.337	0.411
Other reference points (not used)					
F_{MSY}	0.155	0.243	0.298	0.365	0.553
B_{MSY}	1.511	2.131	2.639	3.339	6.275
$F_{Avg[1956-2012]}$	0.207	0.269	0.305	0.341	0.420

Table 26. Decision Table for the ***Area 5CD Base Case*** *model using Performance Measures with Historical Reference Points.* B_{1971} *= the Limit Reference Point (LRP);* $B_{Avg[1956\text{-}2004]}$ *= the Upper Stock Reference (USR);* $F_{Avg[1956\text{-}2004]}$ *= the Limit Removal Rate.*

	Biomass-based measures			Fishing mortality-based measures	
2014 Catch (t)	$P(B_{2015} < B_{2014})$	$P(B_{2015} < B_{1971})$	$P(B_{2015} < B_{Avg[1956\text{-}2004]})$	$P(F_{2014} > F_{2013})$	$P(F_{2014} > F_{Avg[1956\text{-}2004]})$
0	0.124	0.123	0.512	0.000	0.000
50	0.135	0.124	0.515	0.000	0.000
100	0.142	0.125	0.519	0.000	0.000
150	0.152	0.127	0.524	0.000	0.000
200	0.158	0.128	0.526	0.000	0.000
250	0.171	0.131	0.530	0.000	0.000
300	0.178	0.135	0.535	0.000	0.000
350	0.187	0.143	0.542	0.000	0.000
400	0.199	0.148	0.545	0.000	0.000
450	0.215	0.149	0.548	0.000	0.000
500	0.226	0.151	0.552	0.001	0.000
550	0.238	0.152	0.556	0.047	0.000
600	0.244	0.154	0.558	0.161	0.000
650	0.259	0.157	0.563	0.344	0.000
700	0.270	0.157	0.570	0.528	0.000
750	0.282	0.158	0.573	0.678	0.000
800	0.298	0.162	0.579	0.800	0.000
850	0.308	0.165	0.583	0.868	0.001
900	0.318	0.166	0.584	0.917	0.002
950	0.331	0.169	0.587	0.948	0.002
1000	0.347	0.171	0.589	0.958	0.004
1050	0.359	0.176	0.595	0.969	0.004
1100	0.371	0.178	0.597	0.975	0.004
1150	0.385	0.179	0.598	0.982	0.004
1200	**0.396**	**0.182**	**0.600**	**0.988**	**0.005**
1250	0.407	0.183	0.603	0.990	0.010
1300	0.422	0.186	0.607	0.991	0.013
1350	0.432	0.190	0.607	0.993	0.014
1400	0.445	0.191	0.607	0.994	0.018
1450	0.464	0.191	0.609	0.994	0.023
1500	0.475	0.194	0.611	0.996	0.031
1550	0.482	0.198	0.616	0.998	0.034
1600	0.486	0.201	0.618	0.999	0.049
1650	0.495	0.203	0.620	1.000	0.066
1700	0.508	0.207	0.621	1.000	0.078
1750	0.519	0.208	0.624	1.000	0.096
1800	0.524	0.210	0.626	1.000	0.112
1850	0.535	0.211	0.627	1.000	0.132
1900	0.542	0.214	0.631	1.000	0.143
1950	0.550	0.219	0.634	1.000	0.160
2000	0.561	0.223	0.637	1.000	0.170
2050	0.573	0.226	0.641	1.000	0.193
2100	0.585	0.232	0.644	1.000	0.210
2150	0.592	0.234	0.646	1.000	0.231
2200	0.601	0.237	0.647	1.000	0.252
2250	0.609	0.238	0.653	1.000	0.272
2300	0.616	0.240	0.654	1.000	0.298
2350	0.625	0.247	0.658	1.000	0.322
2400	0.641	0.249	0.660	1.000	0.339

Table 27. Decision Table for the ***Area 5AB Base Case*** *model using Performance Measures with Historical Reference Points.* $F_{Avg[1956\text{-}2004]}$ *= the provisional Limit Removal Rate.*

	Fishing mortality-based measures	
2014 Catch (t)	**P($F_{2014} > F_{2013}$)**	**P($F_{2014} > F_{Avg[1956\text{-}2004]}$)**
0	0.000	0.000
50	0.000	0.000
100	0.000	0.004
150	0.001	0.057
200	0.066	0.187
250	0.405	0.372
300	0.738	0.569
350	0.881	0.721
400	0.929	0.817
450	0.963	0.879
500	0.982	0.908
550	0.985	0.937
600	**0.987**	**0.954**
650	0.989	0.967
700	0.993	0.981
750	0.997	0.984
800	0.998	0.988
850	0.999	0.995
900	0.999	0.995
950	0.999	0.995
1000	0.999	0.996
1050	0.999	0.998
1100	0.999	0.999
1150	1.000	0.999
1200	1.000	1.000
1250	1.000	1.000
1300	1.000	1.000
1350	1.000	1.000
1400	1.000	1.000
1450	1.000	1.000
1500	1.000	1.000
1550	1.000	1.000
1600	1.000	1.000

Table 28. *"**Model-averaged**" decision Table for **Area 5CD** using Performance Measures with Historical Reference Points. B_{1971} = the Limit Reference Point (LRP); $B_{Avg[1956-2004]}$ = the Upper Stock Reference (USR); $F_{Avg[1956-2004]}$ = the Limit Removal Rate. See text for scenarios included in this table.*

	Biomass-based measures			Fishing mortality-based measures	
2014 Catch (t)	$P(B_{2015} < B_{2014})$	$P(B_{2015} < B_{1971})$	$P(B_{2015} < B_{Avg[1956-2004]})$	$P(F_{2014} > F_{2013})$	$P(F_{2014} > F_{Avg[1956-2004]})$
0	0.150	0.146	0.512	0.000	0.000
50	0.159	0.147	0.516	0.000	0.000
100	0.168	0.148	0.520	0.000	0.000
150	0.178	0.150	0.525	0.000	0.000
200	0.187	0.151	0.528	0.000	0.000
250	0.198	0.152	0.532	0.000	0.000
300	0.209	0.155	0.536	0.000	0.000
350	0.220	0.157	0.542	0.000	0.000
400	0.233	0.158	0.545	0.000	0.000
450	0.244	0.161	0.549	0.000	0.000
500	0.254	0.163	0.552	0.004	0.000
550	0.267	0.165	0.554	0.038	0.000
600	0.278	0.166	0.557	0.141	0.000
650	0.289	0.167	0.561	0.310	0.000
700	0.297	0.168	0.565	0.514	0.000
750	0.310	0.169	0.568	0.682	0.000
800	0.321	0.172	0.572	0.799	0.001
850	0.334	0.173	0.575	0.872	0.002
900	0.346	0.175	0.577	0.917	0.002
950	0.360	0.177	0.580	0.944	0.003
1000	0.372	0.179	0.584	0.961	0.004
1050	0.382	0.182	0.589	0.973	0.006
1100	0.394	0.184	0.593	0.981	0.007
1150	0.409	0.186	0.595	0.985	0.008
1200	**0.421**	**0.188**	**0.598**	**0.989**	**0.009**
1250	0.431	0.190	0.601	0.992	0.013
1300	0.442	0.192	0.603	0.993	0.015
1350	0.453	0.194	0.607	0.994	0.018
1400	0.464	0.196	0.609	0.996	0.021
1450	0.478	0.199	0.612	0.996	0.028
1500	0.490	0.201	0.615	0.996	0.034
1550	0.500	0.203	0.617	0.997	0.040
1600	0.510	0.205	0.621	0.998	0.048
1650	0.521	0.209	0.625	0.998	0.056
1700	0.532	0.212	0.628	0.999	0.068
1750	0.543	0.213	0.631	0.999	0.080
1800	0.553	0.216	0.635	0.999	0.093
1850	0.564	0.218	0.637	0.999	0.109
1900	0.573	0.220	0.640	0.999	0.122
1950	0.585	0.223	0.643	0.999	0.139
2000	0.595	0.226	0.645	1.000	0.153
2050	0.604	0.229	0.647	1.000	0.171
2100	0.615	0.234	0.650	1.000	0.189
2150	0.621	0.236	0.651	1.000	0.209
2200	0.630	0.238	0.654	1.000	0.227
2250	0.637	0.241	0.659	1.000	0.246
2300	0.645	0.244	0.661	1.000	0.266
2350	0.654	0.248	0.665	1.000	0.285
2400	0.643	0.250	0.667	1.000	0.306

*Table 29. “**Model-averaged**” Decision Table for **Area 5AB** using Performance Measures with Historical Reference Points. $F_{Avg[1956-2004]}$ = the provisional Limit Removal Rate. See text for scenarios included in this table.*

	Fishing mortality-based measures	
2014 Catch (t)	**$P(F_{2014} > F_{2013})$**	**$P(F_{2014} > F_{Avg[1956-2004]})$**
0	0.000	0.000
50	0.000	0.002
100	0.000	0.016
150	0.005	0.069
200	0.077	0.201
250	0.418	0.363
300	0.736	0.517
350	0.882	0.634
400	0.933	0.714
450	0.961	0.774
500	0.976	0.817
550	0.984	0.848
600	**0.988**	**0.877**
650	0.991	0.895
700	0.994	0.911
750	0.996	0.925
800	0.997	0.935
850	0.998	0.948
900	0.998	0.954
950	0.999	0.960
1000	0.999	0.968
1050	0.999	0.975
1100	0.999	0.979
1150	0.999	0.983
1200	1.000	0.985
1250	1.000	0.987
1300	1.000	0.990
1350	1.000	0.990
1400	1.000	0.992
1450	1.000	0.993
1500	1.000	0.994
1550	1.000	0.995
1600	1.000	0.996

FIGURES

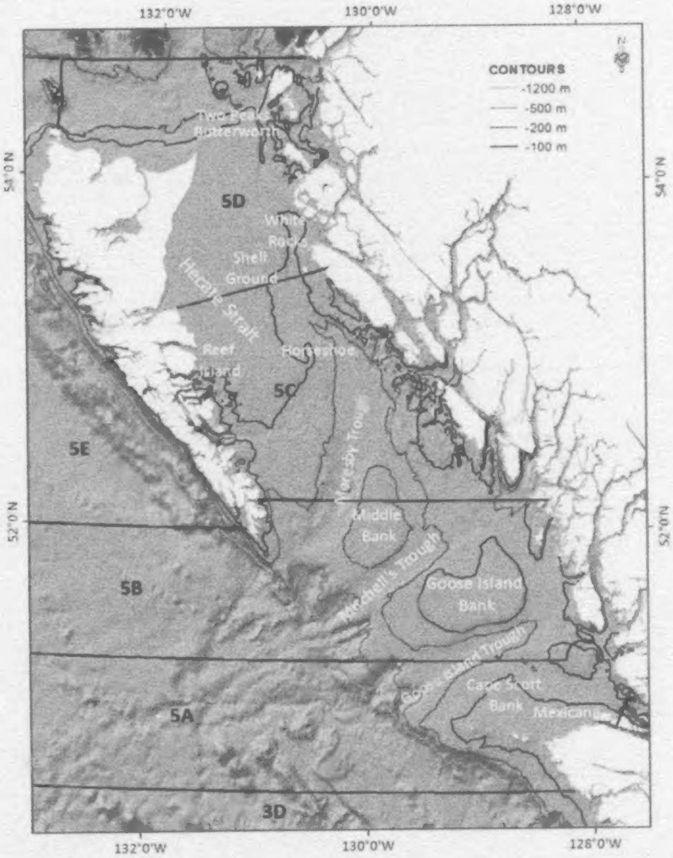

132°0'W
130°0'W
128°0'W
CONTOURS
-1200 m
-500 m
-200 m
-100 m
54°0'N
52°0'N
Two Peaks
Butterworth
5D
White Rocks
Shell Ground
Hecate Strait
Reef Island
Horseshoe
5C
Moresby Trough
5E
Middle Bank
Mitchell's Trough
Goose Island Bank
5B
Goose Island Trough
Cape Scott Bank
Mexicana
5A
3D

Figure 1. Map of the management areas 5AB (Queen Charlotte Sound) and 5CD (Hecate Strait) showing major fishing grounds for Pacific Cod.

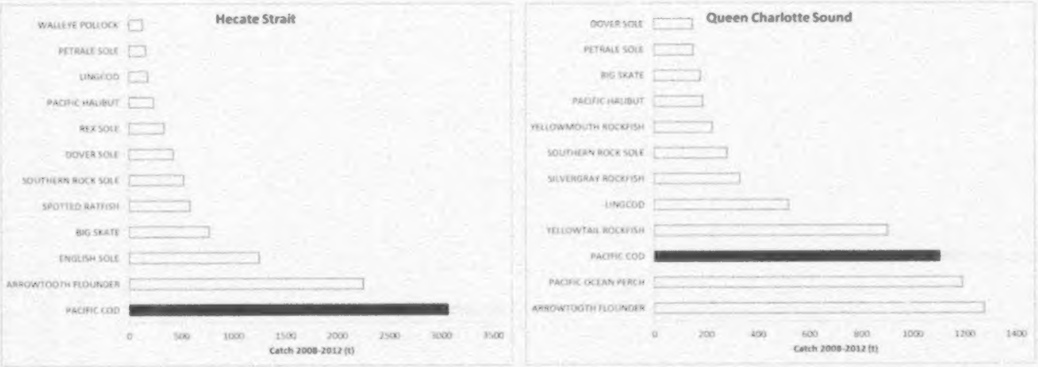


Figure 2. Total catches of species caught in fishing tows that caught 90% of the Pacific Cod catch during the period 2008-2012 in Hecate Strait and Queen Charlotte Sound.

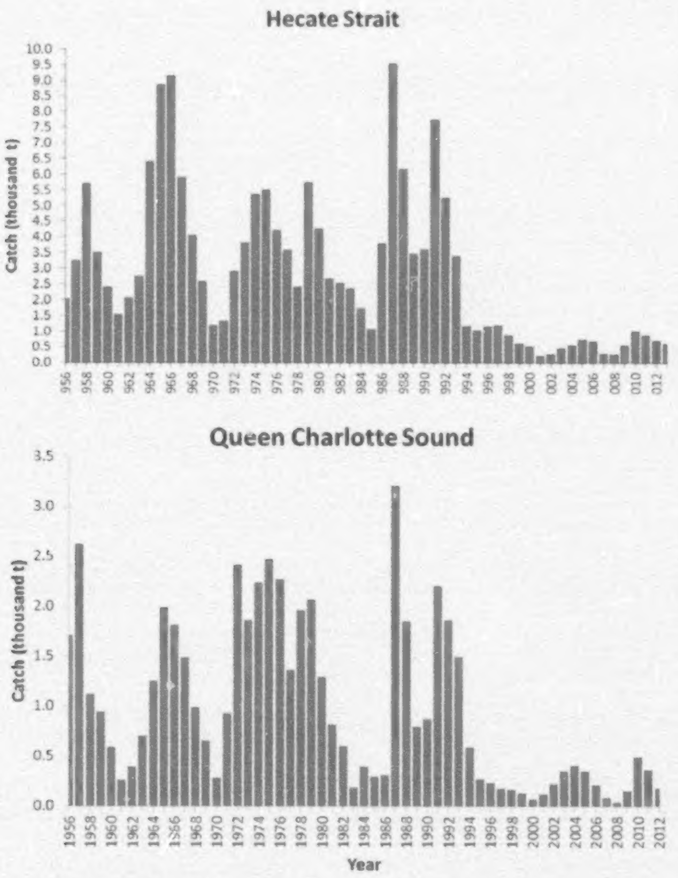
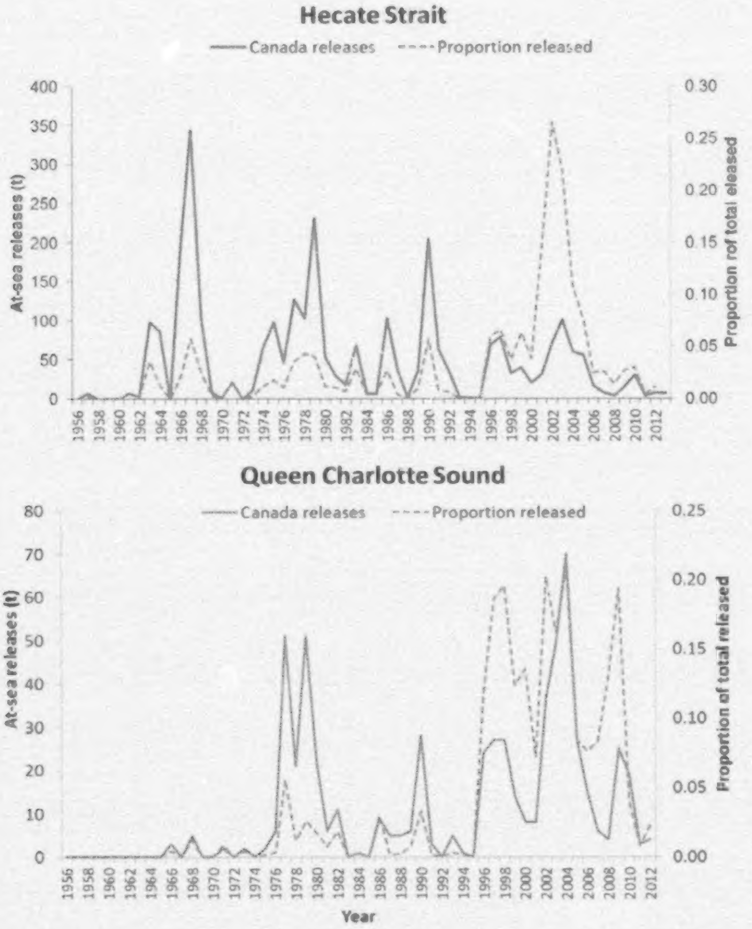


Figure 3. Total catches of Pacific Cod during the period 1956-2012 in Hecate Strait and Queen Charlotte Sound. Catches represent the sum of landings from US and Canadian vessels and estimated at-sea releases from Canadian vessels. See Table 1 for breakdown. Note different scales.

 Hecate Strait

Queen Charlotte Sound

Figure 4. Estimated at-sea releases of Pacific Cod by bottom trawlers in Hecate Strait and Queen Charlotte Sound. Note different scales.

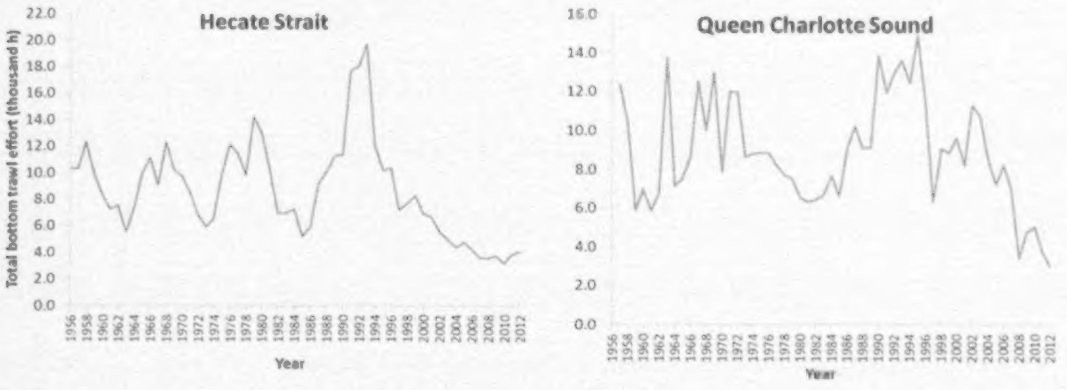


Figure 5. Annual trends in total bottom trawl fishing effort in Hecate Strait and Queen Charlotte Sound (thousands of hours). Note different scales.

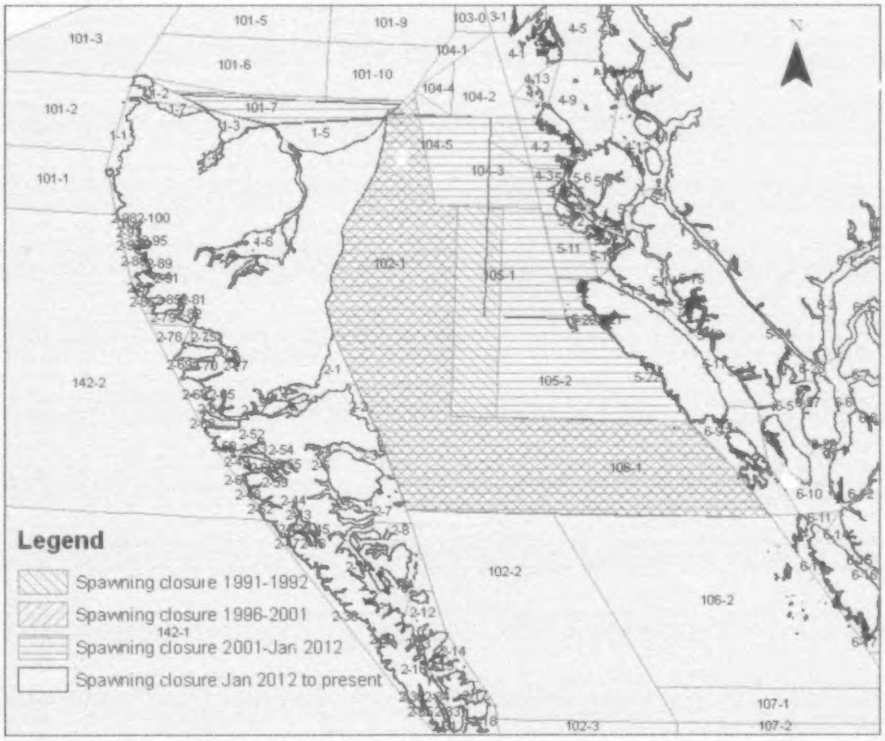

Legend
▧ Spawning closure 1991-1992
▨ Spawning closure 1996-2001
▤ Spawning closure 2001-Jan 2012
☐ Spawning closure Jan 2012 to present
N
101-3
101-5
101-9
103-0
3-1
4-5
104-1
4-1
101-6
101-10
4-13
104-4
104-2
4-9
101-2
1-7
101-7
1-1
1-3
1-5
104-5
4-2
104-3
101-1
5-6
2-100
4-6
5-11
102-1
105-1
142-2
2-1
105-2
5-22
2-52
2-54
108-1
6-10
2-7
2-8
102-2
106-2
2-12
142-1
2-14
107-1
102-3
107-2

Figure 6. Boundaries of spawning closures in Area 5CD. Source: Groundfish Management Plans

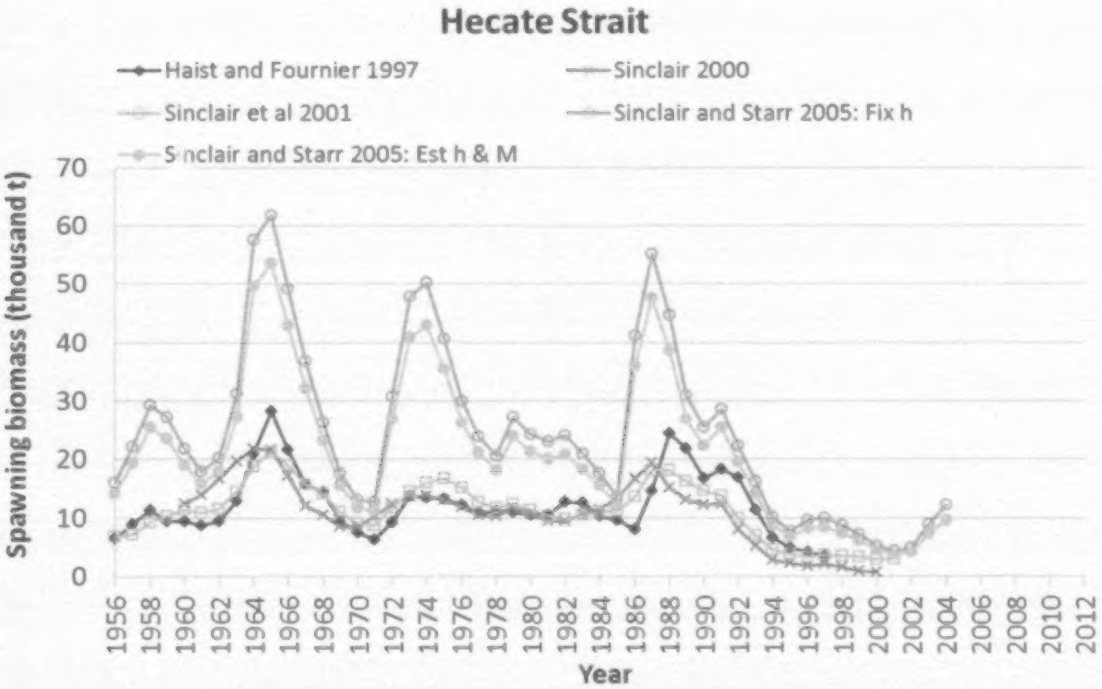


Figure 7. Comparison of biomass estimates for Pacific Cod in Hecate Strait from assessments using Multifan (Haist and Fournier 1997); a surplus production model (Sinclair 2000); a delay difference model with a Ricker stock-recruit function (Sinclair et al. 2001); a delay difference model with a Beverton-Holt stock-recruit function and steepness (h) fixed at 0.75 (Sinclair and Starr 2005); and the same delay difference model with estimated steepness (Sinclair and Starr 2005).

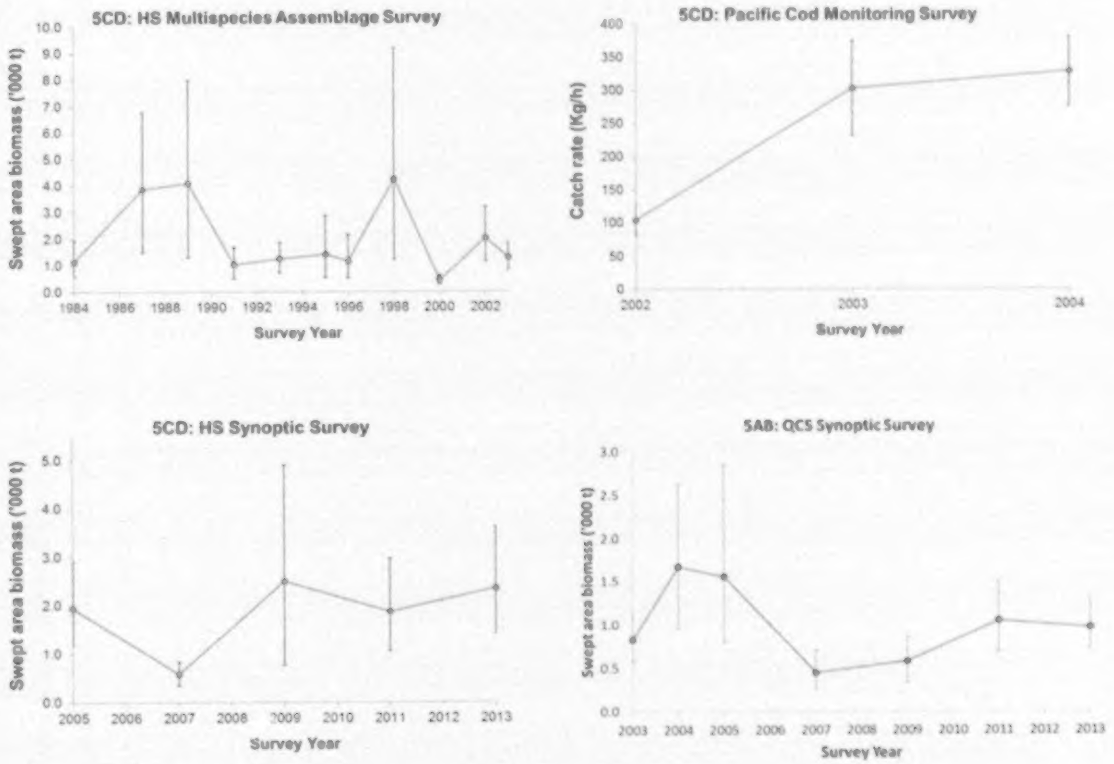


Figure 8. Fishery-independent indices of abundance used in this analysis. All indices are measured as estimated swept area biomass except for the Pacific Cod Monitoring Survey, which is measured in Kg/hr. Error bars show 95% credibility intervals from 1,000 bootstrapped runs for all indices except the Pacific Cod Monitoring Survey, for which error bars show Mean ± C.V.. Note that data from the Pacific Cod Monitoring Survey are only used in bridging analysis runs with terminal year 2004 (see text).

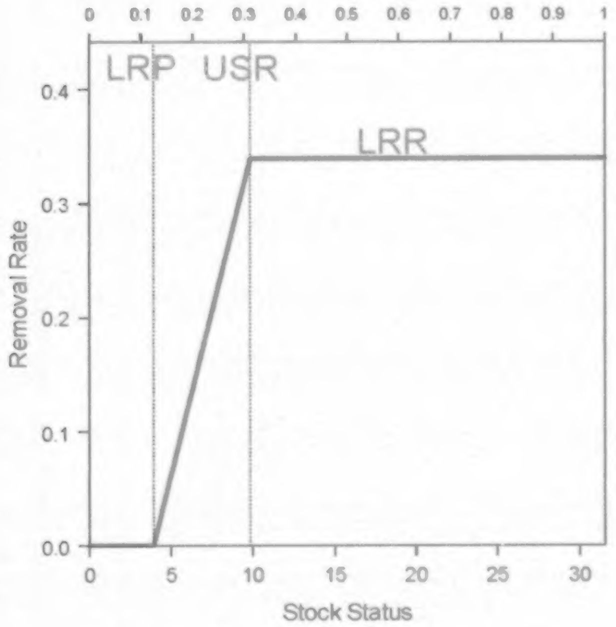


Figure 9. Illustration of an hypothetical harvest control rule consistent with the Precautionary Approach for a hypothetical stock. The biomass-based reference points are shown as vertical lines. The limit removal rate is shown as horizontal blue line. In this illustration, biomass (unspecified units) is shown on the bottom axis, and proportion of unfished biomass is shown on the top axis. LRP = Limit Reference Point; USR = Upper Stock Reference; LRR = Limit Removal Rate.

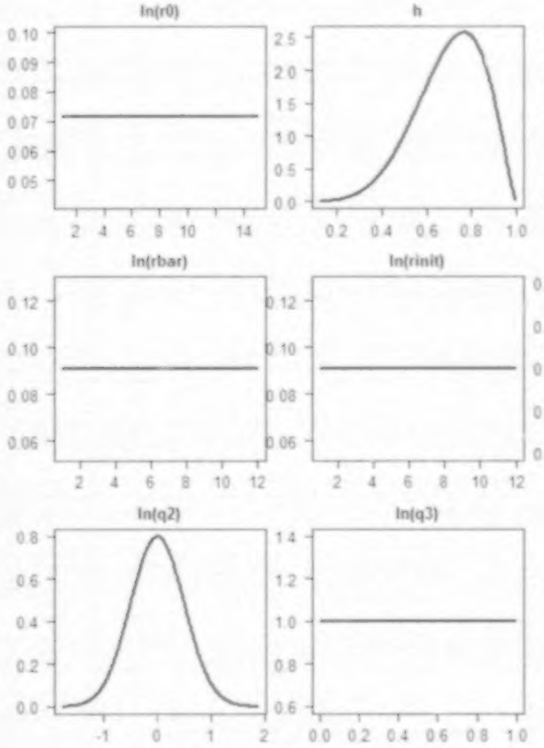


Figure 10. Prior probability distributions used in the Base Case models. Here, rbar = R_{Avg}; rinit = R_{Avg_init}; q_1 = Hecate Strait Assemblage Survey; q_2 = Hecate Strait or Queen Charlotte Sound Synoptic Survey; and q_3 = commercial CPUE data from 1956-1995 for Hecate Strait (or Queen Charlotte Sound).

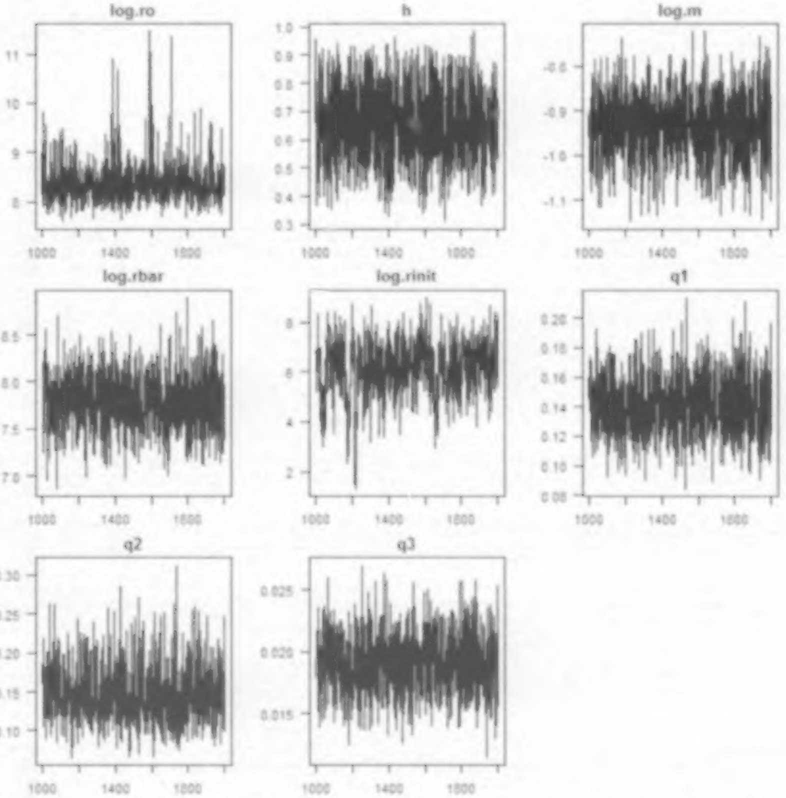


Figure 11. Trace plots of posterior samples for the ***Area 5CD*** *Base case model. Here, log.rbar = ln(R_{Avg}); log.rinit = (R_{Avg_init}); q_1 = Hecate Strait Assemblage Survey; q_2 = Hecate Strait Synoptic Survey; and q_3 = commercial CPUE data from 1956-1995 for Hecate Strait.*

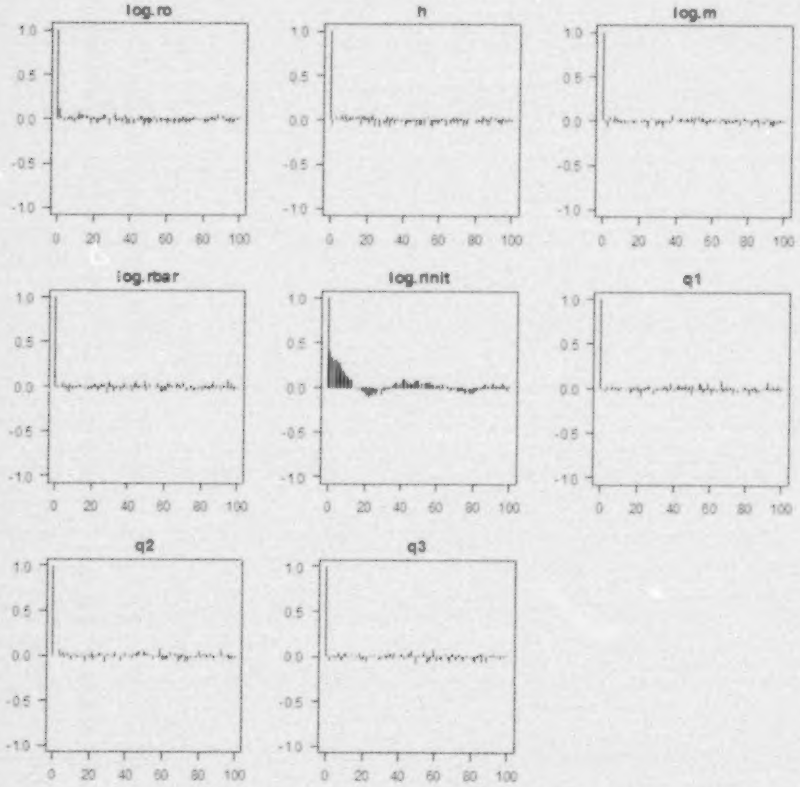


Figure 12. Autocorrelation plots for the ***Area 5CD*** *Base case model. Here, log.rbar = ln(R_{Avg}); log.rinit = ln(R_{Avg_init}); q_1 = Hecate Strait Assemblage Survey; q_2 = Hecate Strait or Queen Charlotte Sound Synoptic Survey; and q_3 = commercial CPUE data from 1956-1995 for Hecate Strait.*

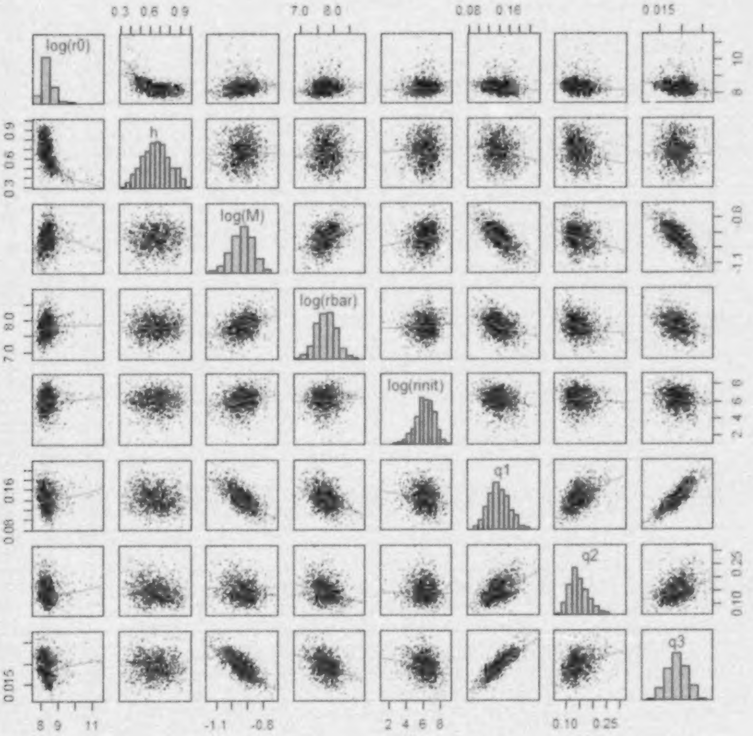


*Figure 13. Pairs plots of posterior samples for the **Area 5CD** Base case model. Here, rbar = R_{Avg}, rinit = R_{Avg_init}, q_1 = Hecate Strait Assemblage Survey; q_2 = Hecate Strait or Queen Charlotte Sound Synoptic Survey; and q_3 = commercial CPUE data from 1956-1995 for Hecate Strait.*

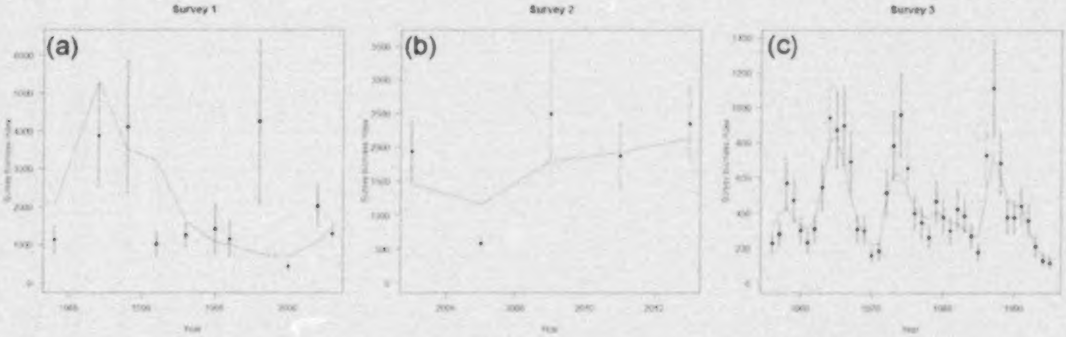


Figure 14. MPD fits (lines) to observed indices of abundance (points) for Area 5CD from: (a) the Hecate Strait Assemblage Survey; (b) the Hecate Strait Synoptic Survey; and (c) the Hecate Strait commercial CPUE data. Annual CVs are shown as error bars.

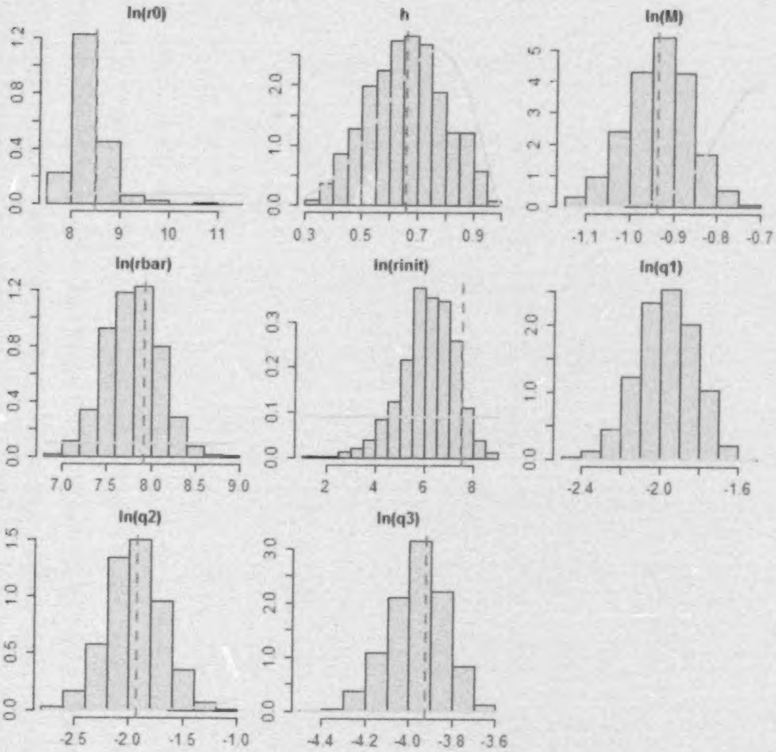


Figure 15. Histograms of posterior samples for the **Area 5CD** *Base case model. Here, rbar = R_{Avg}; rinit = R_{Avg_init}; q_1 = Hecate Strait Assemblage Survey; q_2 = Hecate Strait Synoptic Survey; and q_3 = commercial CPUE data from 1956-1995 for Hecate Strait. Prior probability distributions are shown as green lines (see Figure 10 for complete distributions). MPD estimates are shown as broken red lines.*

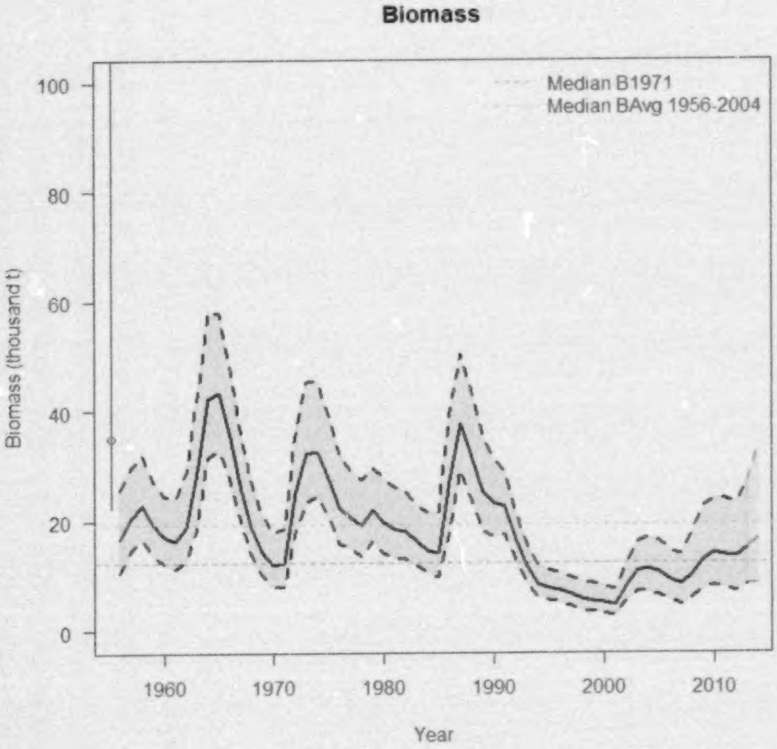


Figure 16. Posterior estimates of biomass (thousand t) for the ***Area 5CD*** *Base Case model with 95% credibility intervals. The 2014 projected biomass and 95% credibility interval is shown in red. The median posterior estimate of* B_0 *is shown as a point (with 95% credibility interval as error bars). The median posterior estimate of the USR is shown as a green broken line. The median posterior estimate of the LRP is shown as a red broken line.*

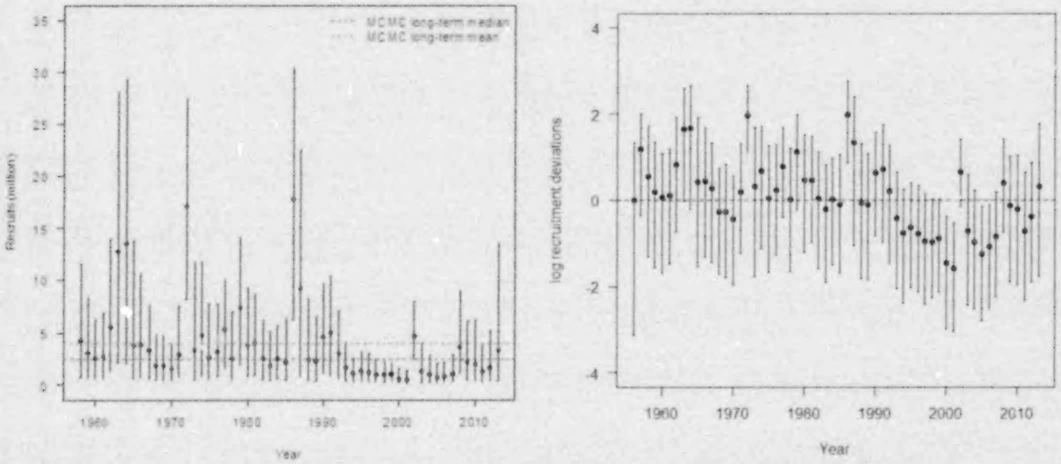


*Figure 17. Posterior estimates of age-2 recruits (L) and log recruitment deviations (R) for the **Area 5CD** Base Case model with 95% credibility intervals.*

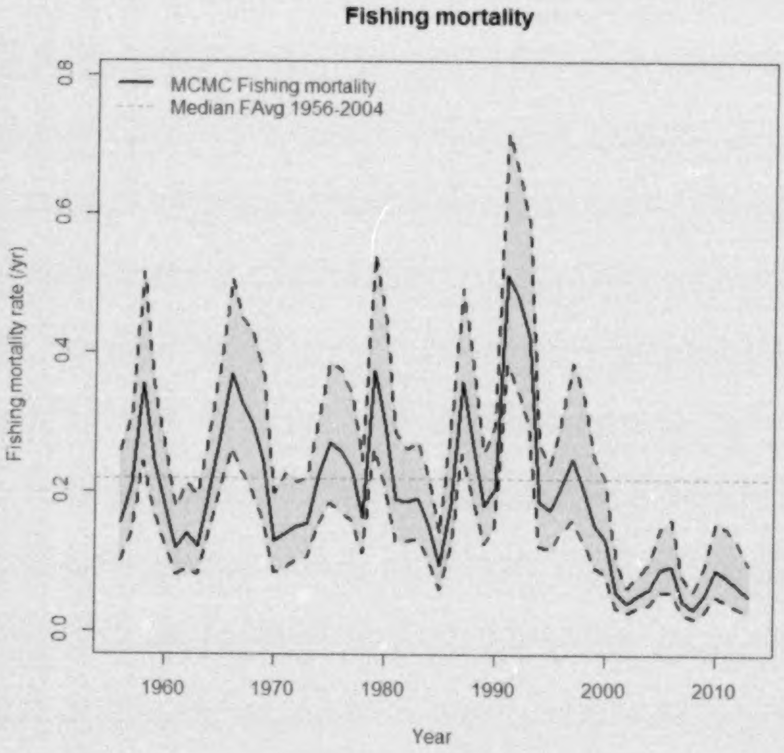


Figure 18. Posterior estimates of fishing mortality for the ***Area 5CD*** *Base Case model with 95% credibility intervals. The median estimate of the LRR, $F_{Avg[1956\text{-}2004]}$ is shown as a red broken line.*

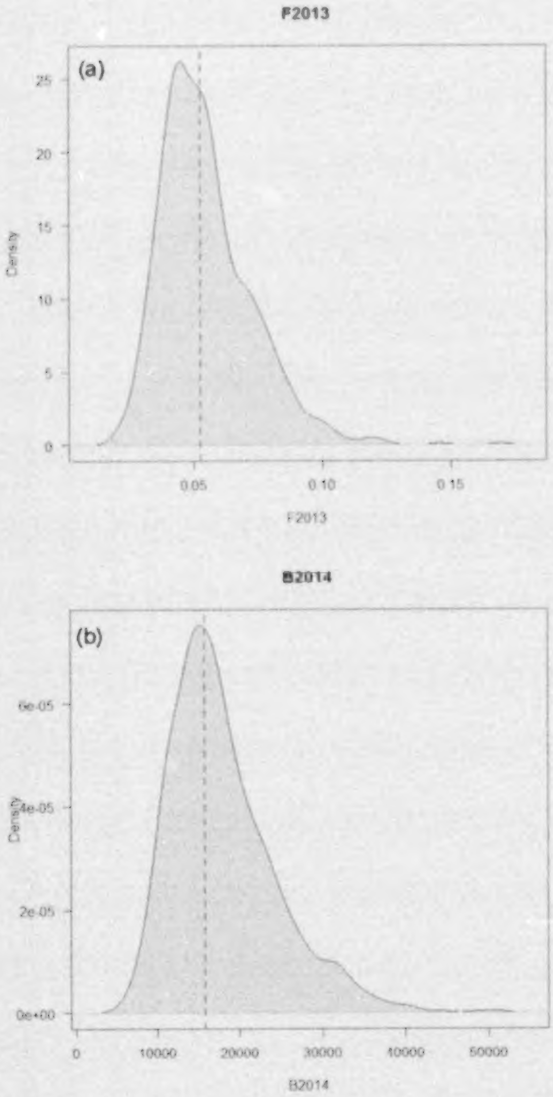


*Figure 19. Posterior density plots of benchmarks F_{2013} and B_{2014} for the **Area 5CD** Base Case model. The MPD estimate is shown as a red broken line.*

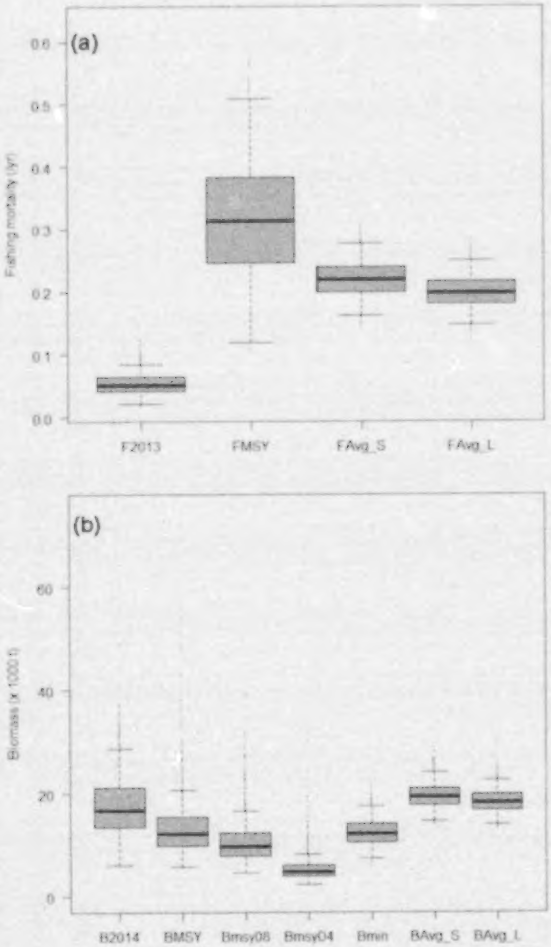


Figure 20. Posterior estimates of alternative reference points from the **Area 5CD** Base Case model *. F2013 = F_{2013}; FMSY = F_{MSY}; FAvg_S = $F_{Avg[1956\text{-}2004]}$; FAvg_L = $F_{Avg[1956\text{-}2012]}$; B2014 = B_{2014}; BMSY = B_{MSY}; BMSY08 = $0.8B_{MSY}$; BMSY04 = $0.4B_{MSY}$; BAvg_S = $B_{Avg[1956\text{-}2004]}$; BAvg_L = $B_{Avg[1956\text{-}2012]}$. See text and Table 12 for definitions. Posterior medians are shown as thick horizontal lines; boxes show the interquartile range (IQR); whiskers show 0.95 * IQR. Outliers are shown as points.*

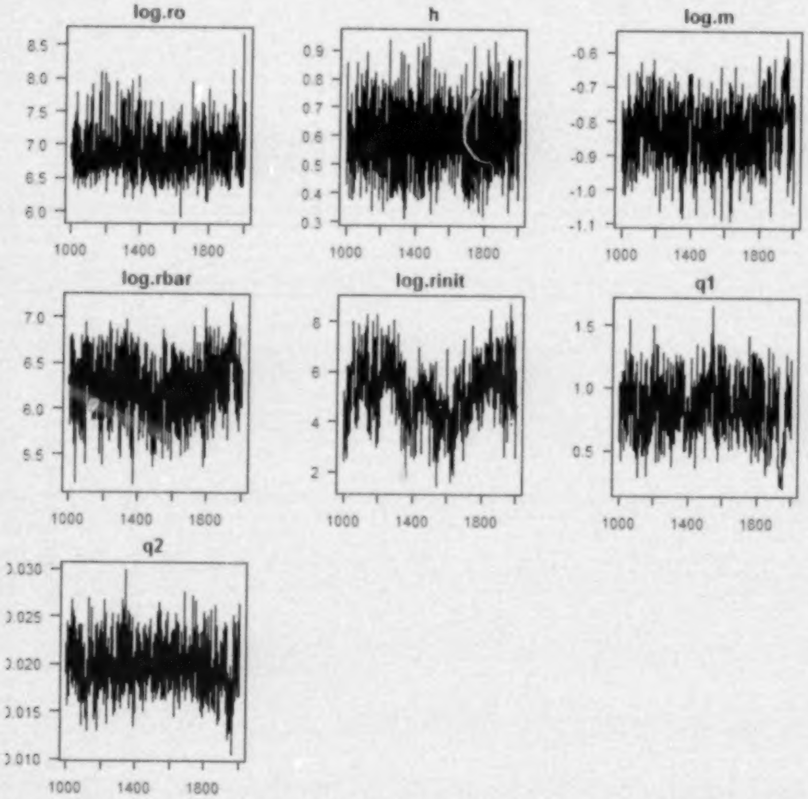


Figure 21. Trace plots of posterior samples for the Area 5AB Base case model. Here, log.rbar = ln(RAvg); log.rinit = ln(RAvg_init); q1 = Queen Charlotte Sound Synoptic Survey; and q2 = commercial CPUE data from 1956-1995 for Queen Charlotte Sound.

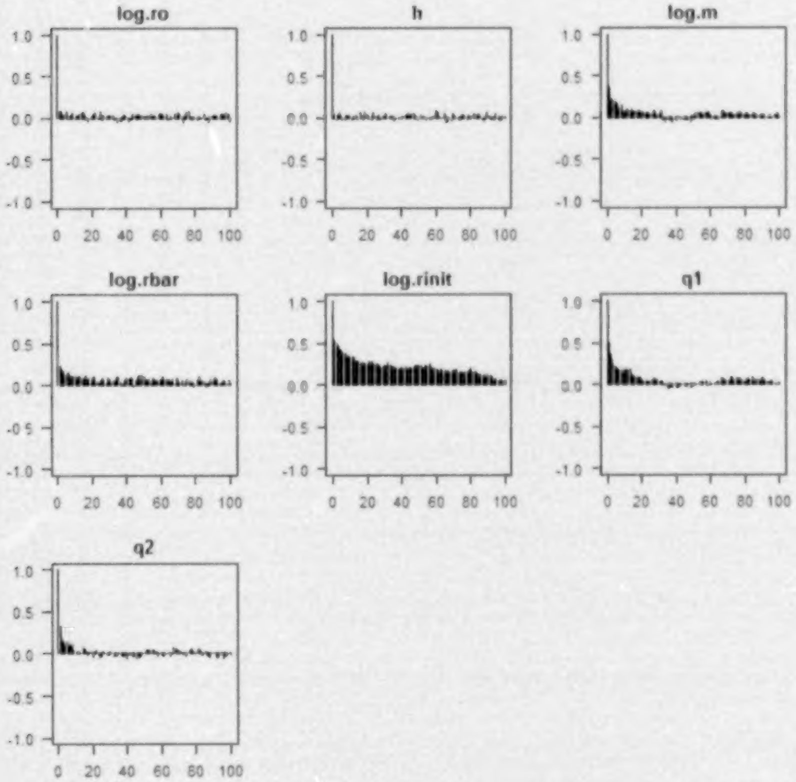


Figure 22. Autocorrelation plots of posterior samples for the ***Area 5AB*** *Base case model. Here, log.rbar = ln(R_{Avg}); log.rinit = ln(R_{Avg_init}); q_1 = Queen Charlotte Sound Synoptic Survey; and q_2 = commercial CPUE data from 1956-1995 for Queen Charlotte Sound.*

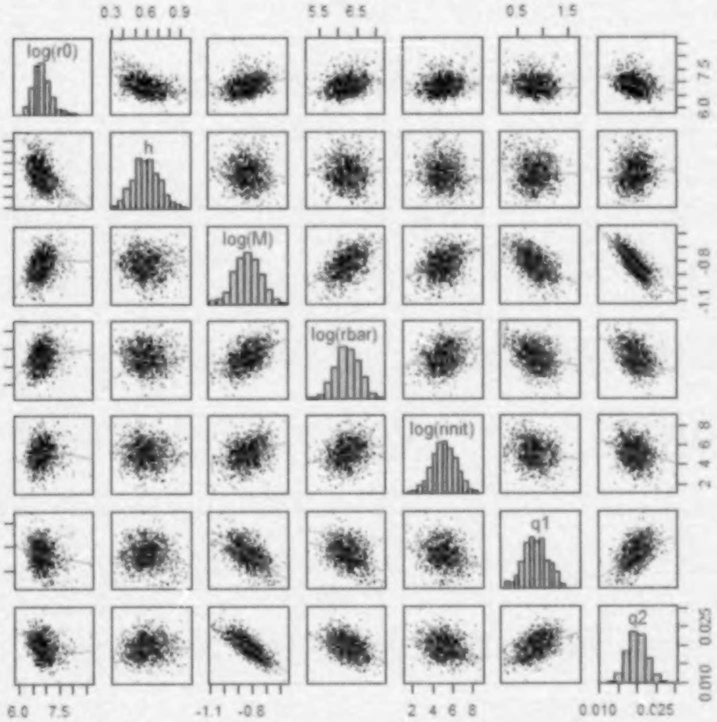


*Figure 23. Pairs plots of posterior samples for the **Area 5AB** Base case model. Here, log(rbar) = ln(R_{Avg}); log(rinit) = ln(R_{Avg_init}); q_1 = Queen Charlotte Sound Synoptic Survey; and q_2 = commercial CPUE data from 1956-1995 for Queen Charlotte Sound.*

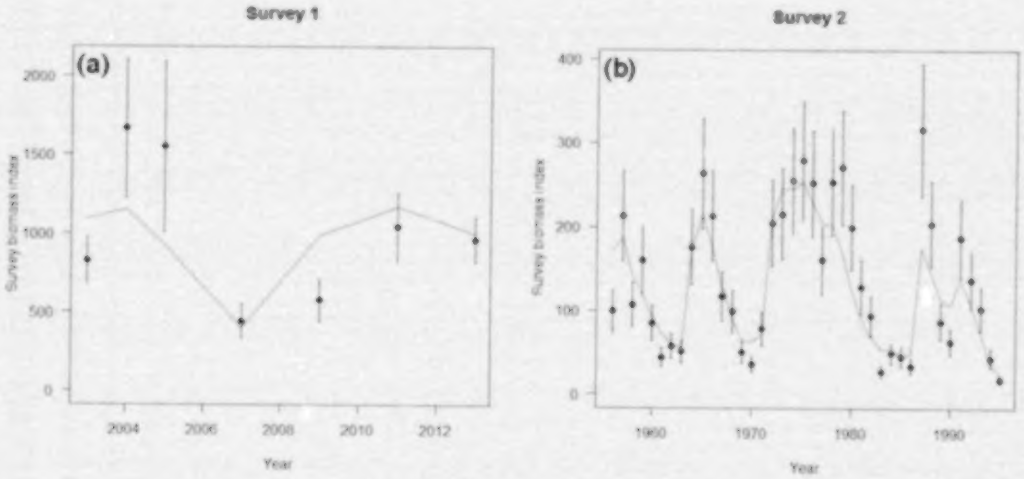


Figure 24. MPD fits (lines) to observed indices of abundance (points) from the Area 5AB Base Case model from: (a) the Queen Charlotte Sound Synoptic Survey; and (b) the Queen Charlotte Sound commercial CPUE data. Annual CVs are shown as error bars.

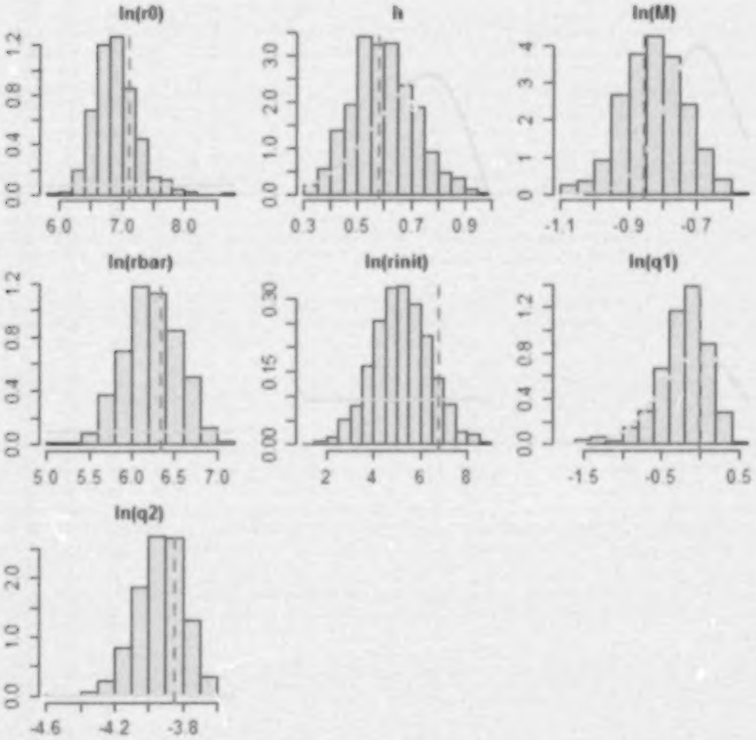


Figure 25. Histograms of posterior samples for the ***Area 5AB*** *Base case model. Here, rbar = R_{Avg}; rinit = R_{Avg_init}; q_1 = Queen Charlotte Sound Synoptic Survey; and q_2 = commercial CPUE data from 1956-1995 for Queen Charlotte Sound. Prior probability distributions are shown as green lines (see Figure 10 for complete distributions). MPD estimates are shown as broken red lines.*

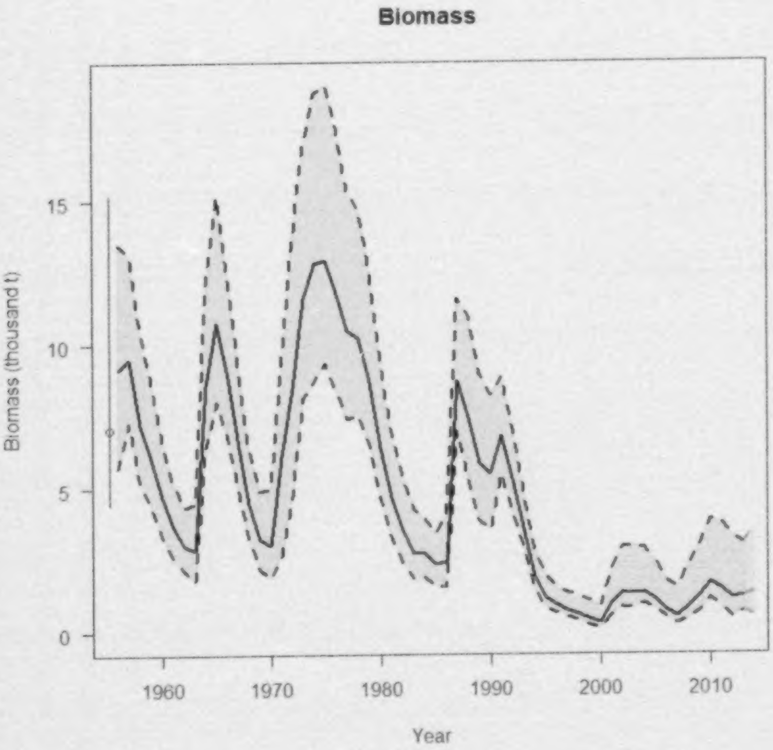


Figure 26. Posterior estimates of biomass (thousand t) for the ***Area 5AB*** *Base Case model with 95% credibility intervals. The 2014 projected biomass and 95% credibility interval is shown in red. The median posterior estimate of B_0 is shown as a point (with 95% credibility interval as error bars).*

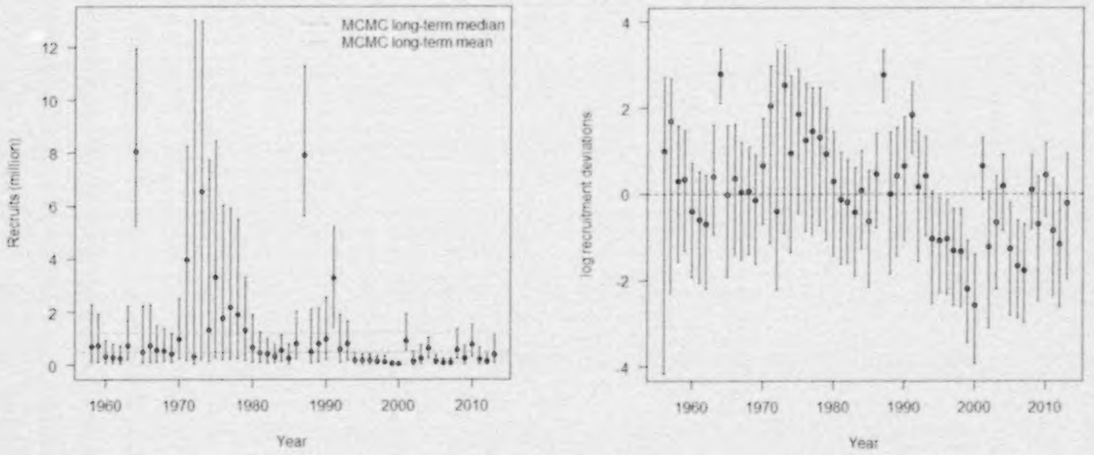


Figure 27. Posterior estimates of age-2 recruits (L) and log recruitment deviations (R) for the ***Area 5AB*** *Base Case model with 95% credibility intervals.*

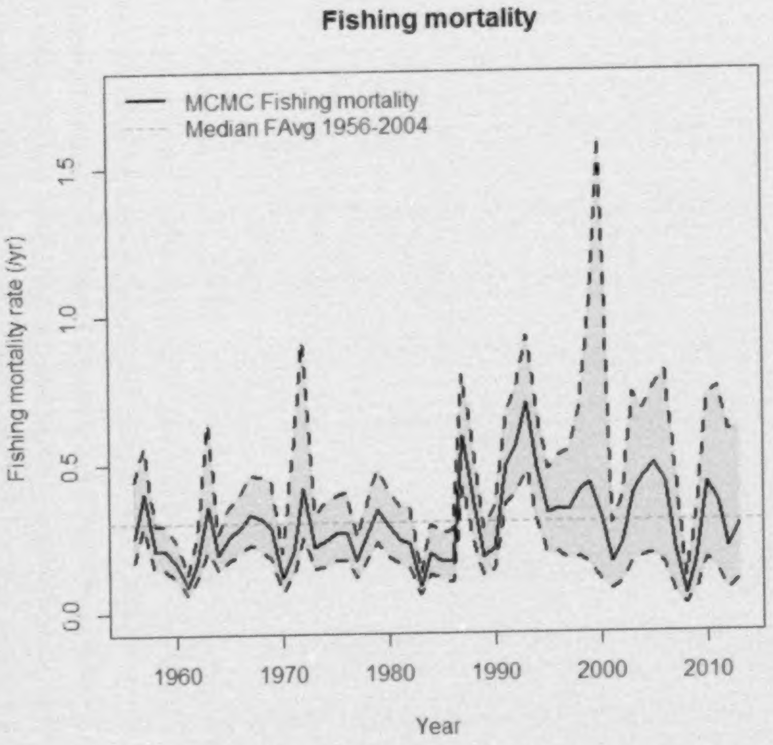


Figure 28. Posterior estimates of fishing mortality for the ***Area 5AB*** *Base Case model with 95% credibility intervals. The median estimate of the provisional LRR,* $F_{Avg[1956\text{-}2004]}$ *is shown as a red broken line.*

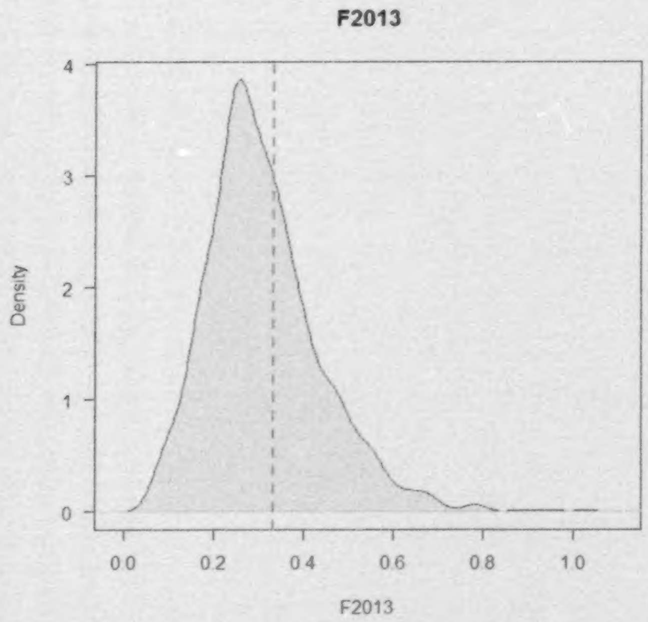


Figure 29. Posterior density plots of benchmarks F2013 for the Area 5AB Base Case model. The MPD estimate is shown as a red broken line.

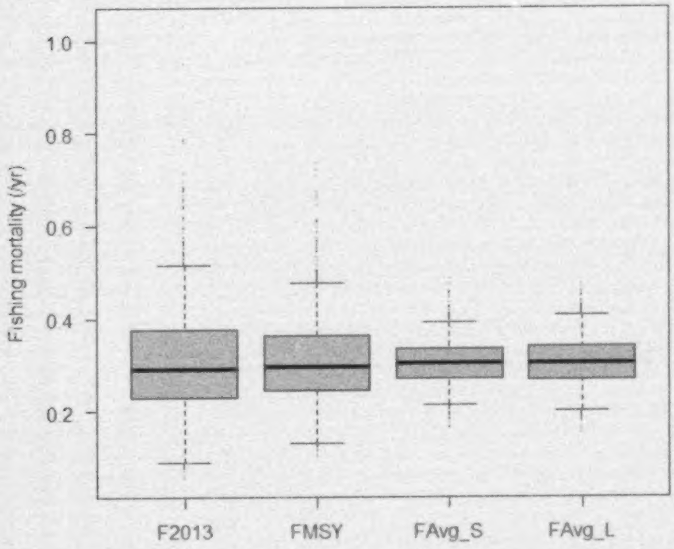


Figure 30. Posterior estimates of alternative F-based reference points from the ***Area 5AB*** *Base Case model. F2013 =* F_{2013}*; FMSY =* F_{MSY}*; FAvg_S =* $F_{Avg[1956\text{-}2004]}$*; FAvg_L =* $F_{Avg[1956\text{-}2012]}$*. Posterior medians are shown as thick horizontal lines; boxes show the interquartile range (IQR); whiskers show 0.95 * IQR. Outliers are shown as points.*

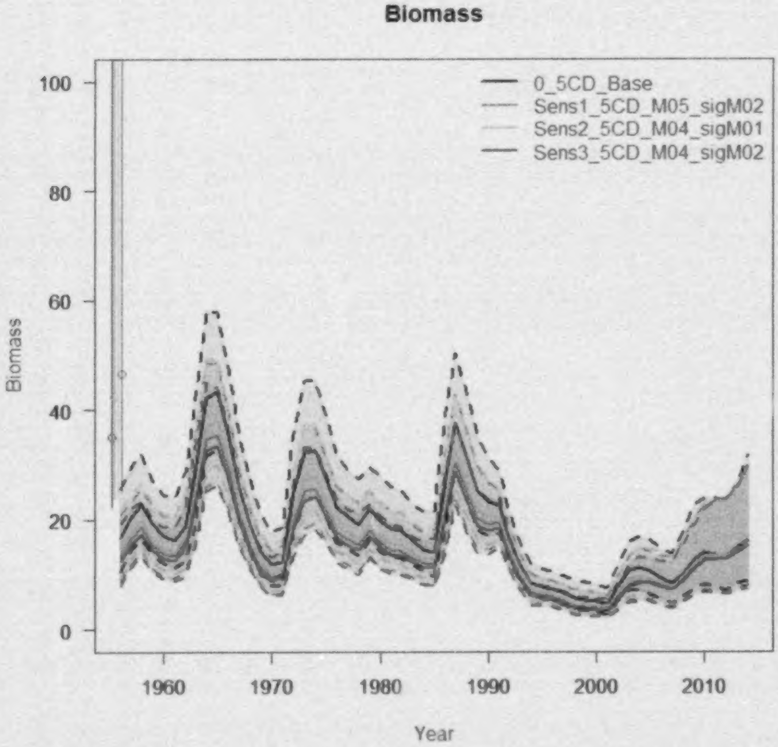


Figure 31. Posterior estimates of biomass (thousand t) with 95% credibility intervals for the ***Area 5CD*** *Base Case model (black) and tests of sensitivity to the prior probability distribution for ln(M). Median posterior estimates of B_0 are shown as points (with 95% credibility interval as error bars).*

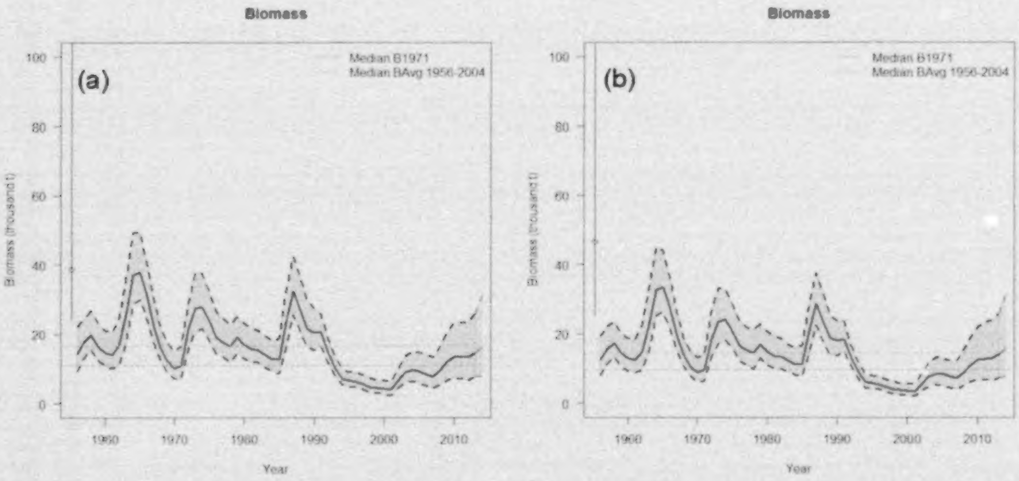


Figure 32. Posterior estimates of biomass (thousand t) showing median posterior USR (green line) and LRP (red line) for the ***Area 5CD*** *tests of sensitivity to the probability distribution for ln(M) , with: (a) mean = 0.4, SD = 0.1; and (b) mean = 0.4, SD = 0.2. The median posterior estimate of the USR is shown as a green broken line. The median posterior estimate of the LRP is shown as a red broken line. Median posterior estimates of B_0 are shown as points (with 95% credibility interval as error bars).*

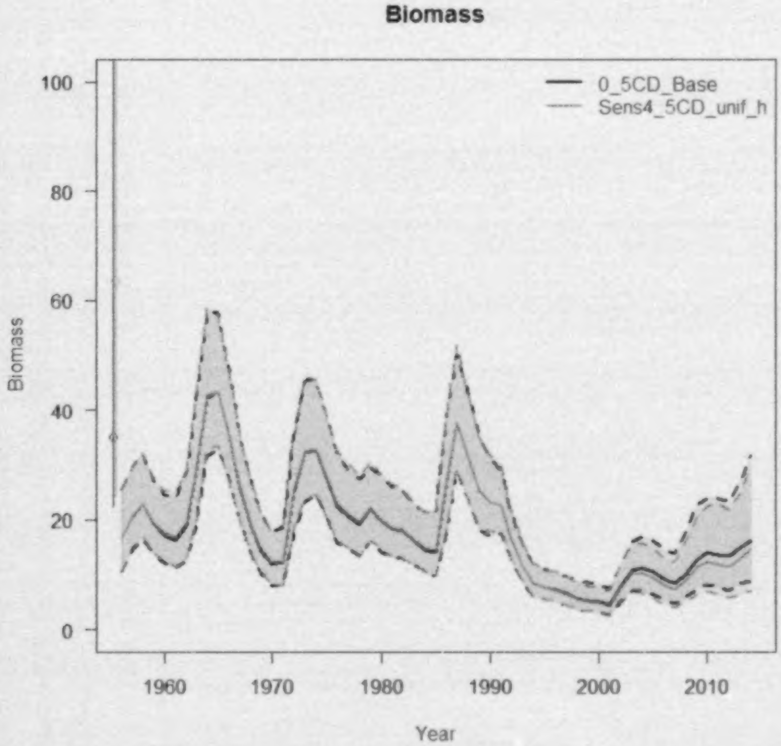


Figure 33. Posterior estimates of biomass (thousand t) with 95% credibility intervals for the ***Area 5CD*** *Base Case model (black) and test of sensitivity to the prior probability distribution for steepness (h). Median posterior estimates of B_0 are shown as points (with 95% credibility interval as error bars).*

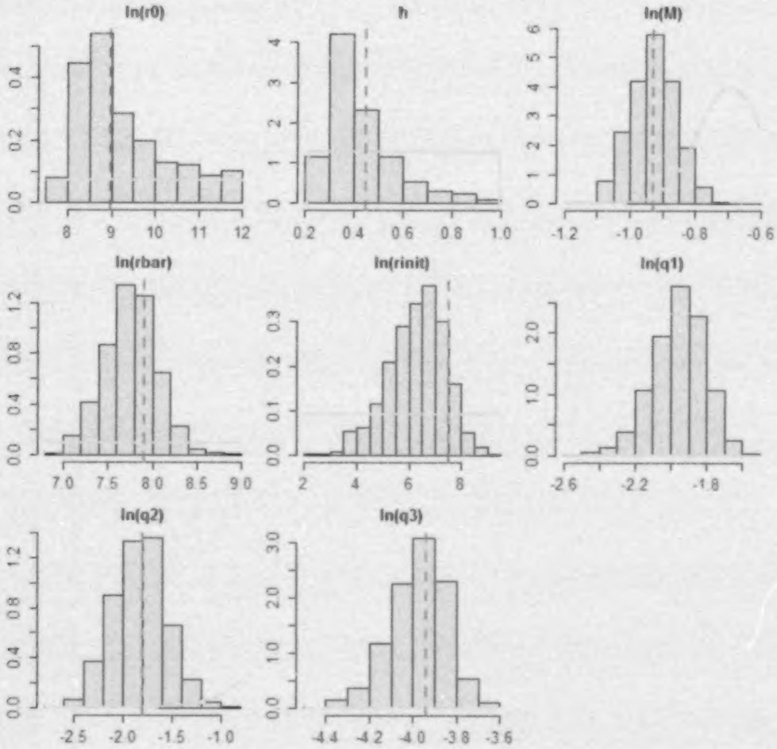


Figure 34. Histograms of posterior samples for the ***Area 5CD*** *sensitivity test to the prior probability distribution for steepness. Here, rbar = R_{Avg}; rinit = R_{Avg_init}; q_1 = Hecate Strait Assemblage Survey; q_2 = Hecate Strait Synoptic Survey; and q_3 = commercial CPUE data from 1956-1995 for Hecate Strait. Prior probability distributions are shown as green lines (see Figure 10 for complete distributions). MPD estimates are shown as broken red lines.*

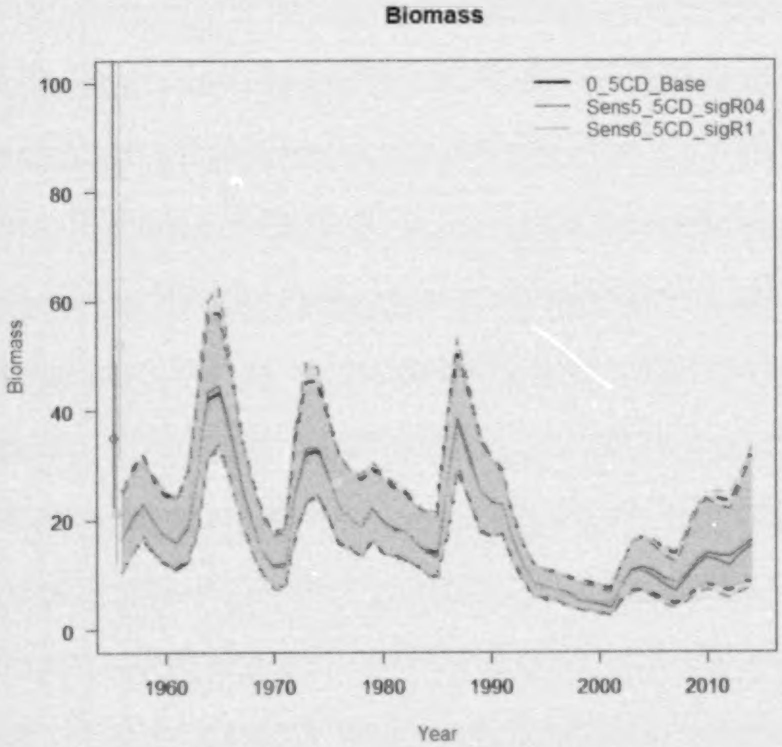


Figure 35. Posterior estimates of biomass (thousand t) with 95% credibility intervals for the ***Area 5CD*** *Base Case model (black) and tests of sensitivity to the prior probability distribution for the value of σ_R. Median posterior estimates of B_0 are shown as points (with 95% credibility interval as error bars).*

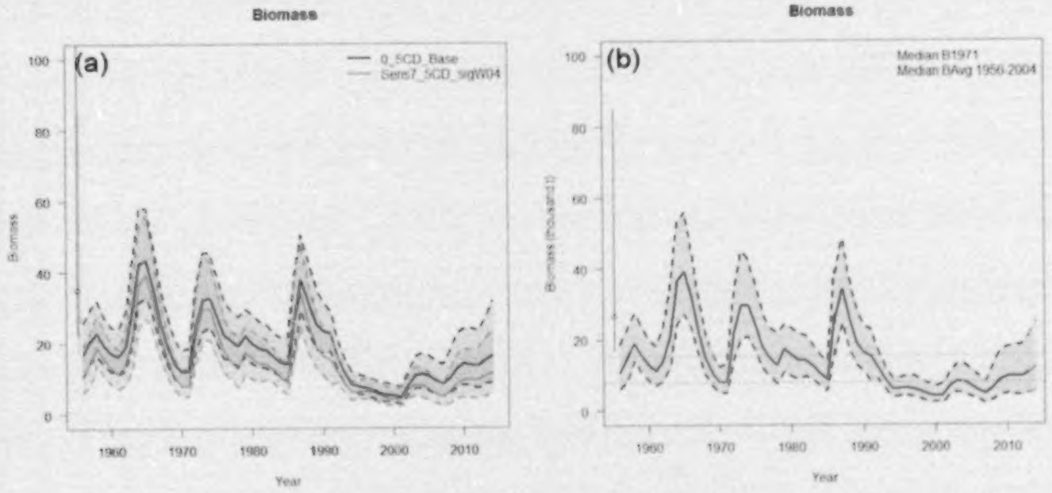


Figure 36. (a) Posterior estimates of biomass (thousand t) with 95% credibility intervals for the ***Area 5CD*** *Base Case model (black) and test of sensitivity to the prior probability distribution for the value of σ_w. and (b) Posterior estimates of biomass (thousand t) showing median posterior USR (green line) and LRP (red line) for the test of sensitivity to the probability distribution for σ_w. Median posterior estimates of B_0 are shown as points (with 95% credibility interval as error bars).*

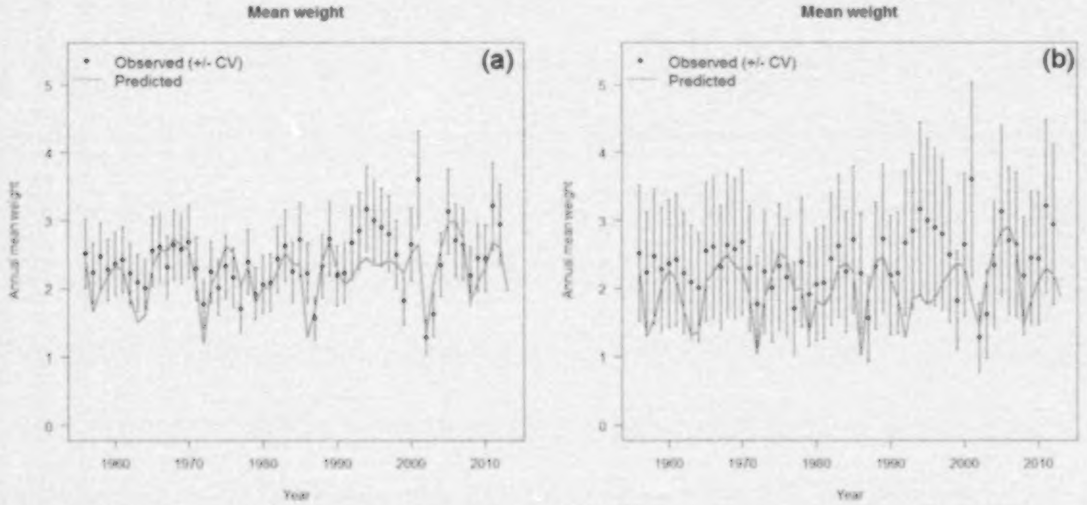


Figure 37. MPD fit to the mean weight data for: (a) the ***Area 5CD*** *Base Case model; and (b) the test of sensitivity to the probability distribution for σ_w. Predicted mean weights are shown as a red line and observations are shown as points. Error bars on mean weight observations represent the fixed CV, based on: a) σ_W =0.2; and b) σ_W =0.4.*

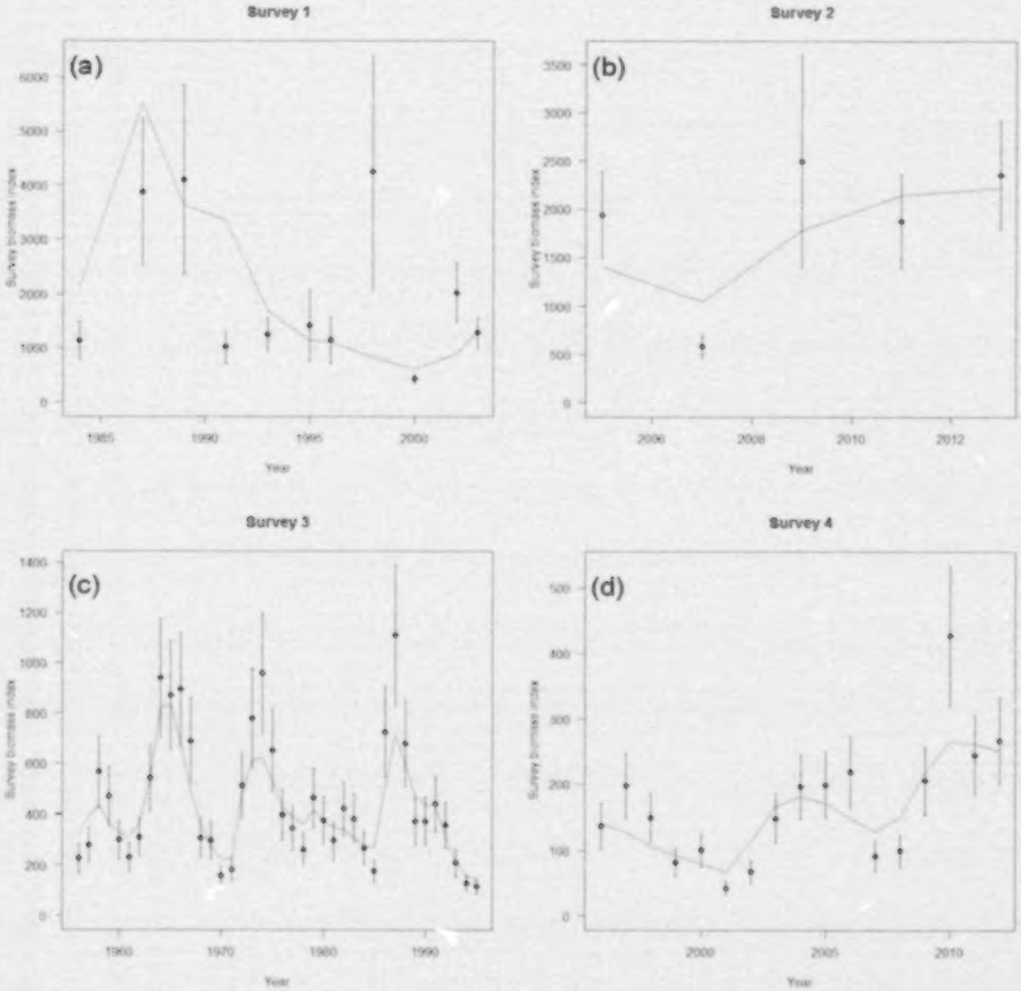


Figure 38. MPD fits (lines) to observed indices of abundance (points) for Area 5CD from: (a) the Hecate Strait Assemblage Survey; (b) the Hecate Strait Synoptic Survey; (c) the Hecate Strait commercial CPUE data, 1956-1995; and (d) the Hecate Strait commercial CPUE data, 1996-2012 Annual CVs are shown as error bars.

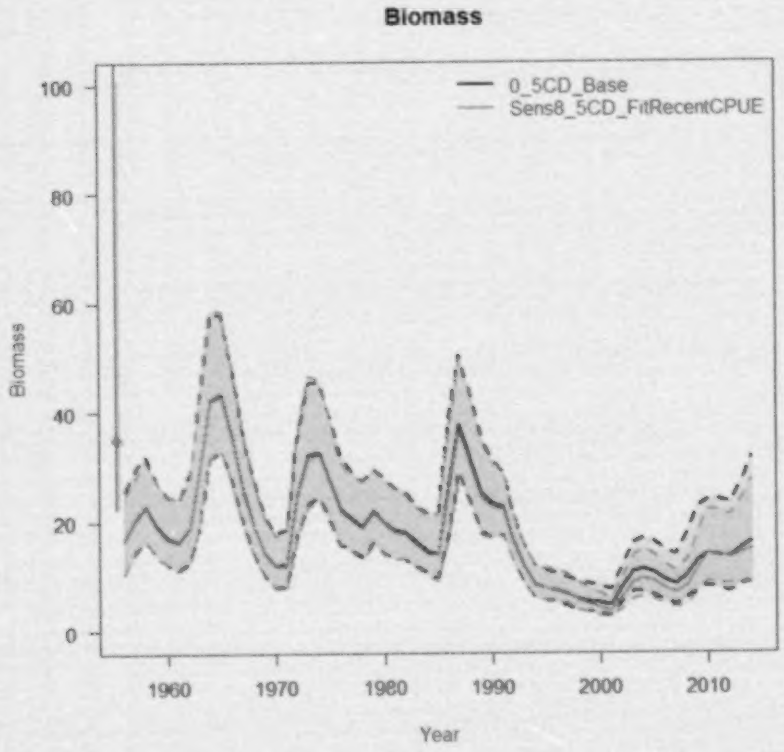


Figure 39. Posterior estimates of biomass (thousand t) with 95% credibility intervals for the Area 5CD Base Case model (black) and tests of sensitivity to the addition of the commercial CPUE data from 1996-2012. Median posterior estimates of B_0 are shown as points (with 95% credibility interval as error bars).

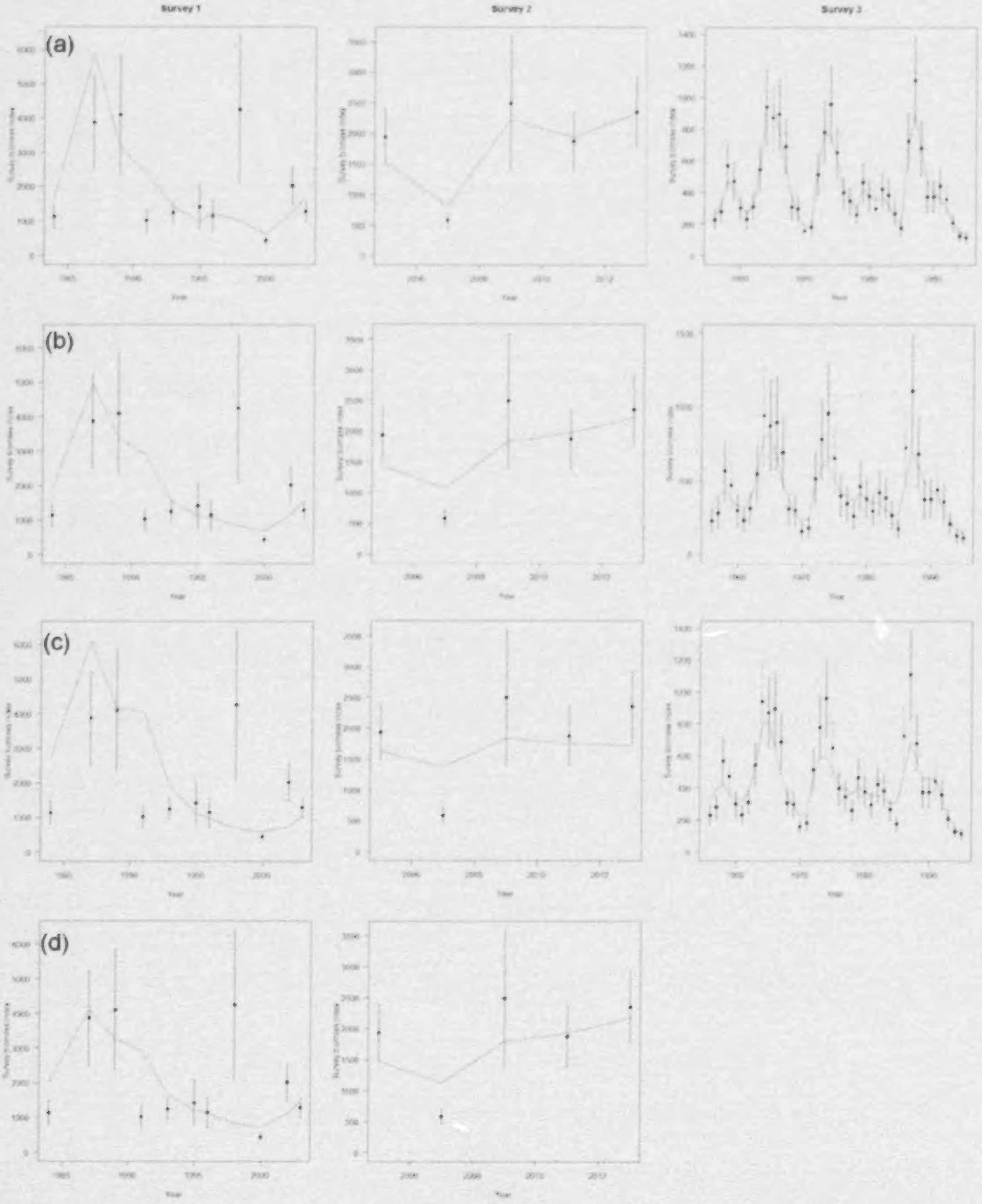


*Figure 40. MPD fits (lines) to observed indices of abundance (points) for **Area 5CD** for: (Left) the Hecate Strait Assemblage Survey; (Centre) the Hecate Strait Synoptic Survey; and (Right) the Hecate Strait commercial CPUE data, 1956-1995 from sensitivity tests with: (a) $\sigma_O = 0.15$; (b) $CV = 0.35$ for the commercial CPUE index of abundance; (c) use conditional MPD estimate of σ_j; and (d) remove commercial CPUE data.*

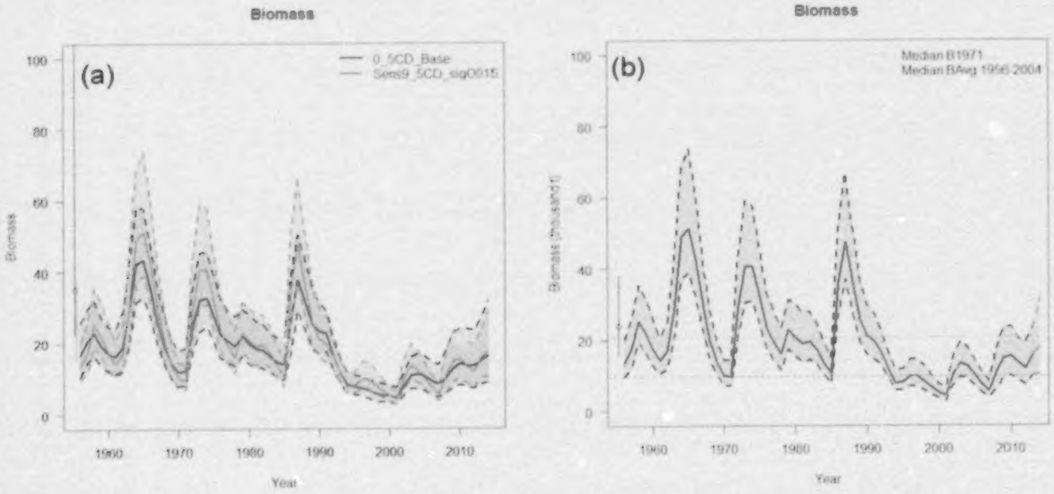


Figure 41. (a) Posterior estimates of biomass (thousand t) with 95% credibility intervals for the ***Area 5CD*** *Base Case model (black) and test of sensitivity with $\sigma_O = 0.15$; and (b) Posterior estimates of biomass (thousand t) showing median posterior USR (green line) and LRP (red line) for the test of sensitivity with $\sigma_O = 0.15$. Median posterior estimates of B_0 are shown as points (with 95% credibility interval as error bars).*

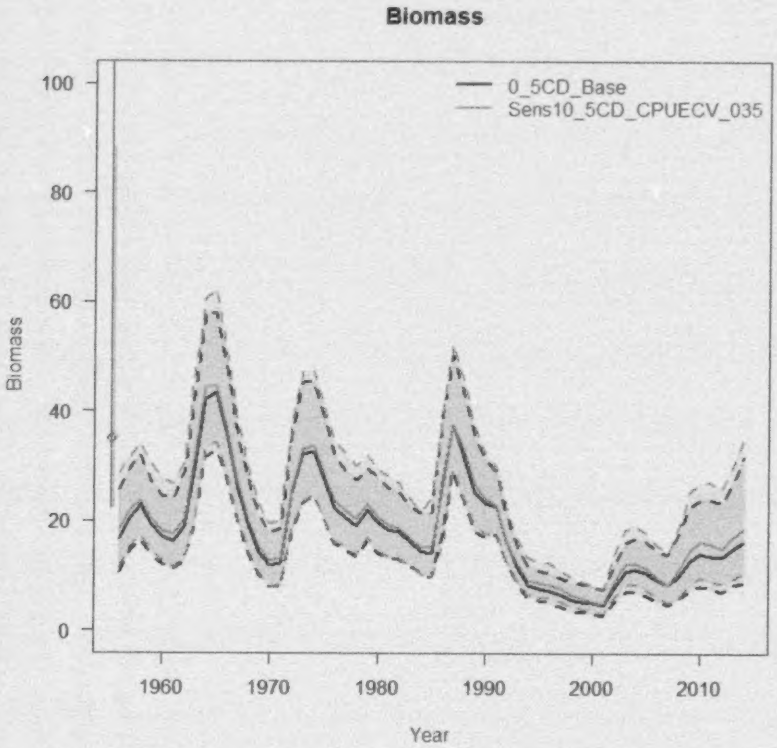


Figure 42Figure 42. Posterior estimates of biomass (thousand t) with 95% credibility intervals for the ***Area 5CD*** *Base Case model (black) and tests of sensitivity to setting $CV_{i,j}$ for the commercial CPUE data =0.35. Median posterior estimates of B_0 are shown as points (with 95% credibility interval as error bars).*

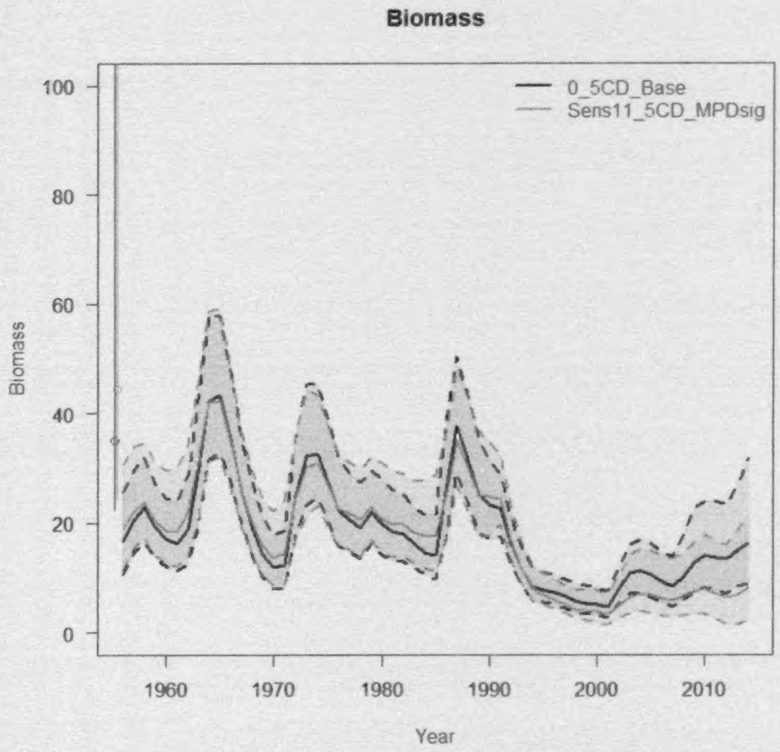


Figure 43. Posterior estimates of biomass (thousand t) with 95% credibility intervals for the ***Area 5CD*** *Base Case model (black) and tests of sensitivity to using the conditional MPD estimate of σ_j in the objective function. Median posterior estimates of B_0 are shown as points (with 95% credibility interval as error bars).*

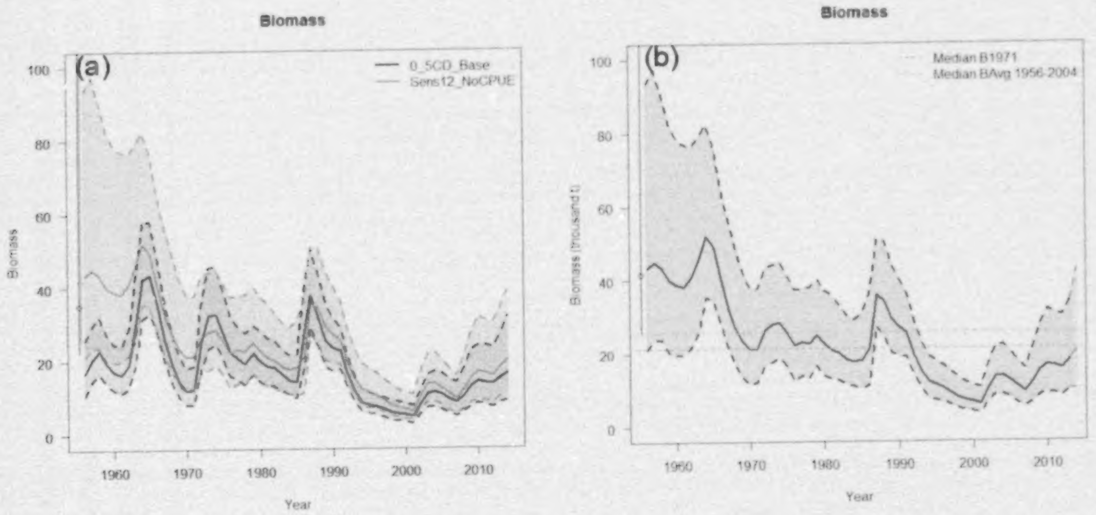


Figure 44. (a) Posterior estimates of biomass (thousand t) with 95% credibility intervals for the ***Area 5CD*** *Base Case model (black) and test of sensitivity with the commercial CPUE data removed; and (b) Posterior estimates of biomass (thousand t) showing median posterior USR (green line) and LRP (red line) for the test of sensitivity with the commercial CPUE data removed. Median posterior estimates of B_0 are shown as points (with 95% credibility interval as error bars).*

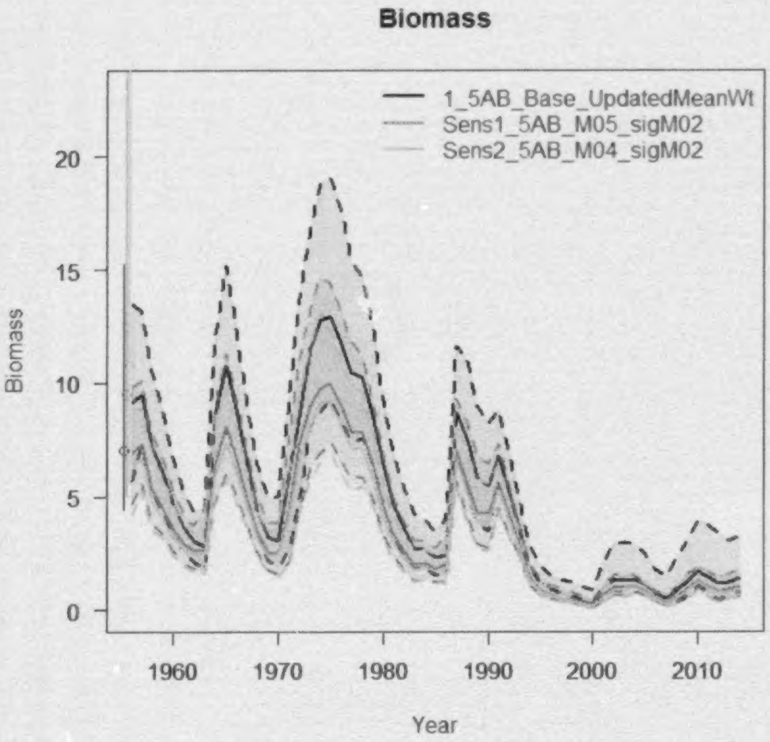


Figure 45. Posterior estimates of biomass (thousand t) with 95% credibility intervals for the ***Area 5AB*** *Base Case model (black) and tests of sensitivity to the prior probability distribution for ln(M). Median posterior estimates of B_0 are shown as points (with 95% credibility interval as error bars).*

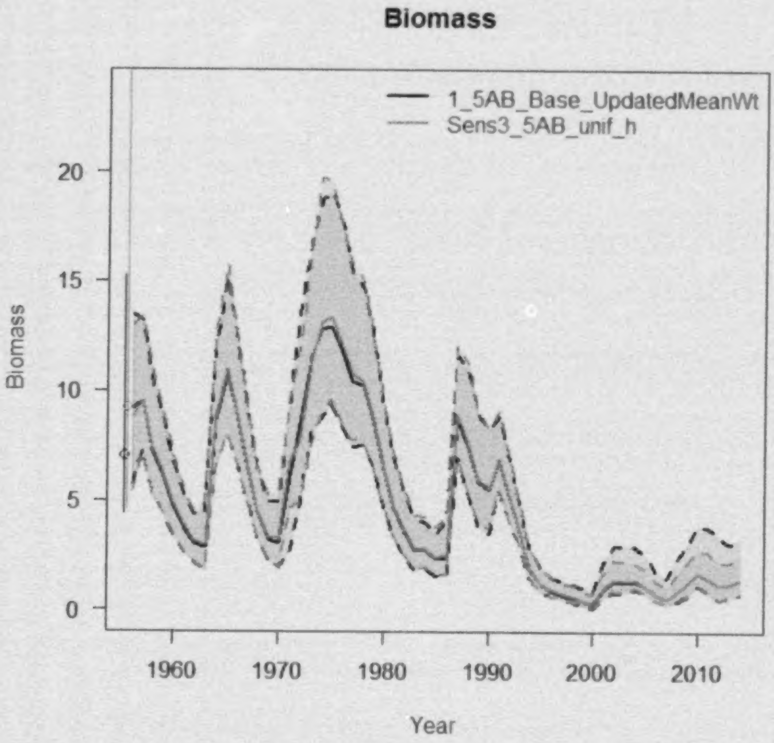


Figure 46. Posterior estimates of biomass (thousand t) with 95% credibility intervals for the ***Area 5AB*** *Base Case model (black) and test of sensitivity to the prior probability distribution for steepness (h). Median posterior estimates of B_0 are shown as points (with 95% credibility interval as error bars).*

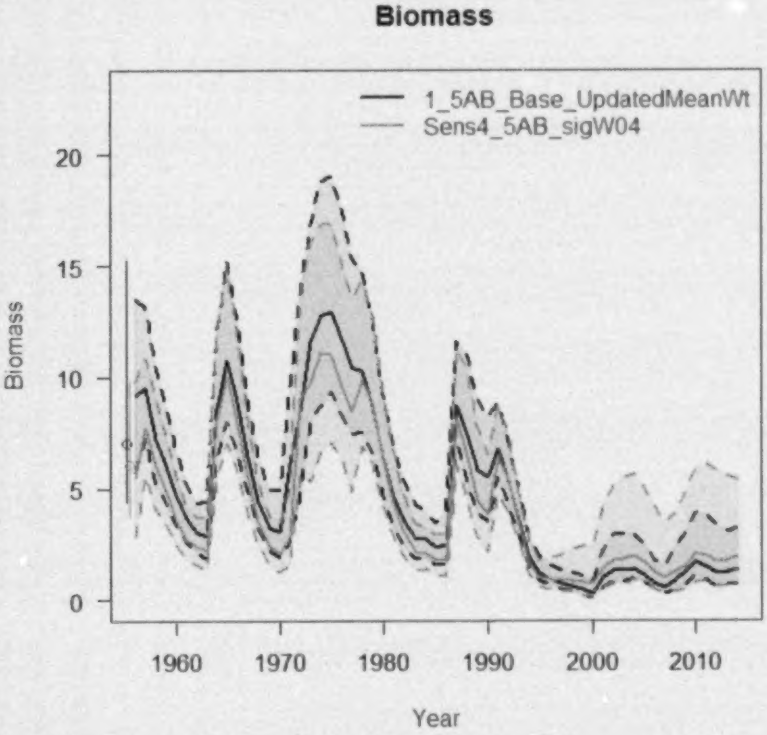


Figure 47. Posterior estimates of biomass (thousand t) with 95% credibility intervals for the ***Area 5AB*** *Base Case model (black) and test of sensitivity to the prior probability distribution for the value of* σ_w*. Median posterior estimates of* B_0 *are shown as points (with 95% credibility interval as error bars).*

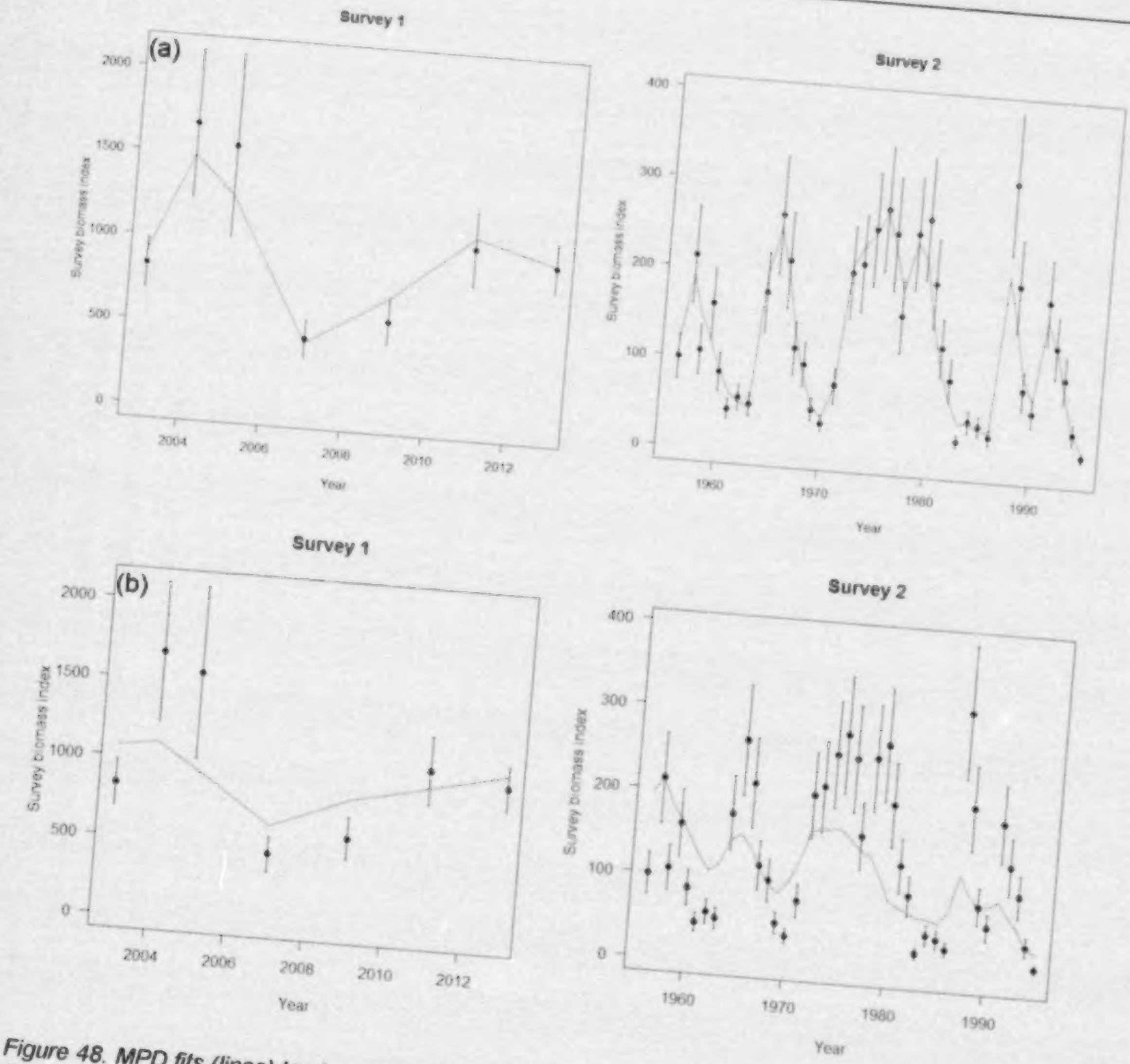


Figure 48. MPD fits (lines) to observed indices of abundance (points) for ***Area 5AB*** *for: (Left) the Queen Charlotte Sound Synoptic Survey; and (Right) the Queen Charlotte Sound commercial CPUE data, 1956-1995 from sensitivity tests with: (a)* $\sigma_O = 0.15$*; and (b) use conditional MPD estimate of* σ_j*.*

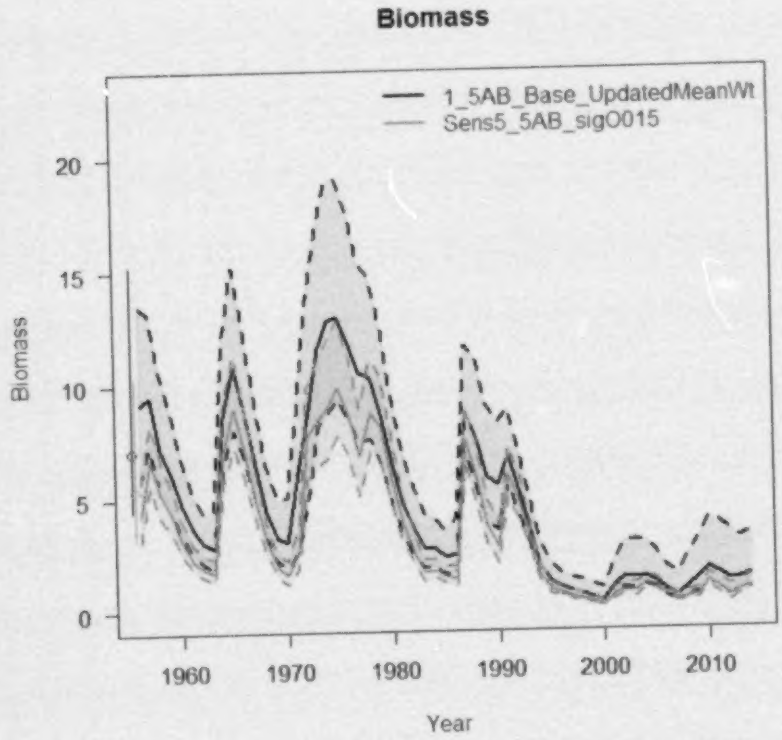


Figure 49 Posterior estimates of biomass (thousand t) with 95% credibility intervals for the ***Area 5AB*** *Base Case model (black) and test of sensitivity with $\sigma_O = 0.15$. Median posterior estimates of B_0 are shown as points (with 95% credibility interval as error bars).*

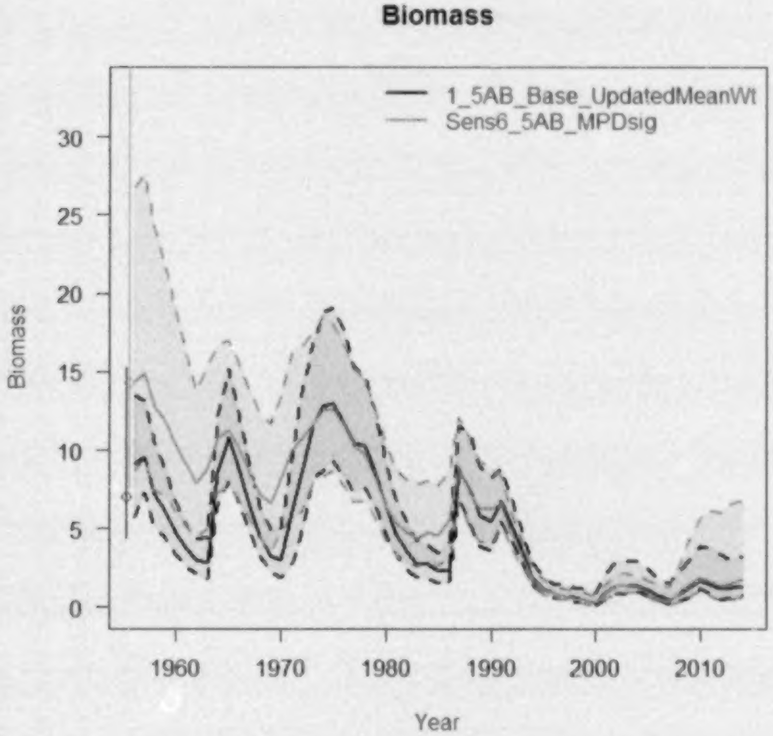


Figure 50. Posterior estimates of biomass (thousand t) with 95% credibility intervals for the ***Area 5AB*** *Base Case model (black) and test of sensitivity using the conditional MPD estimate of σ_l. Median posterior estimates of B_0 are shown as points (with 95% credibility interval as error bars).*

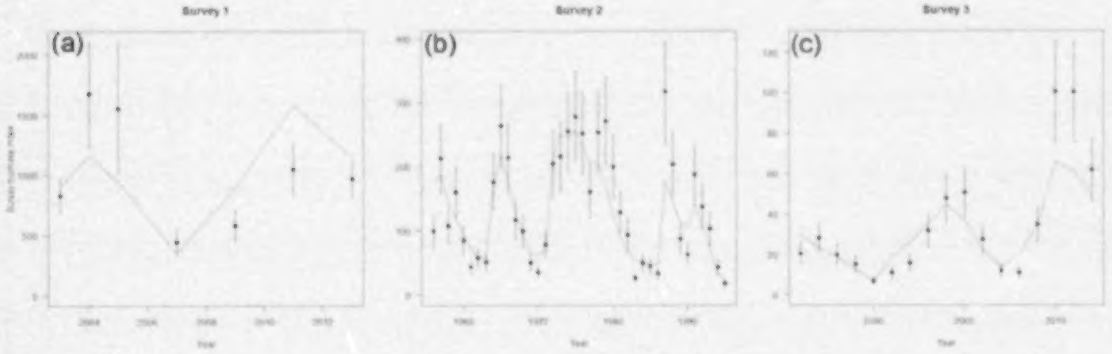


Figure 51. MPD fits (lines) to observed indices of abundance (points) for **Area 5AB** from: (a) the Queen Charlotte Sound Synoptic Survey; (b) the Queen Charlotte Sound commercial CPUE data, 1956-1995; and (c) the Queen Charlotte Sound commercial CPUE data, 1996-2012 . Annual CVs are shown as error bars.

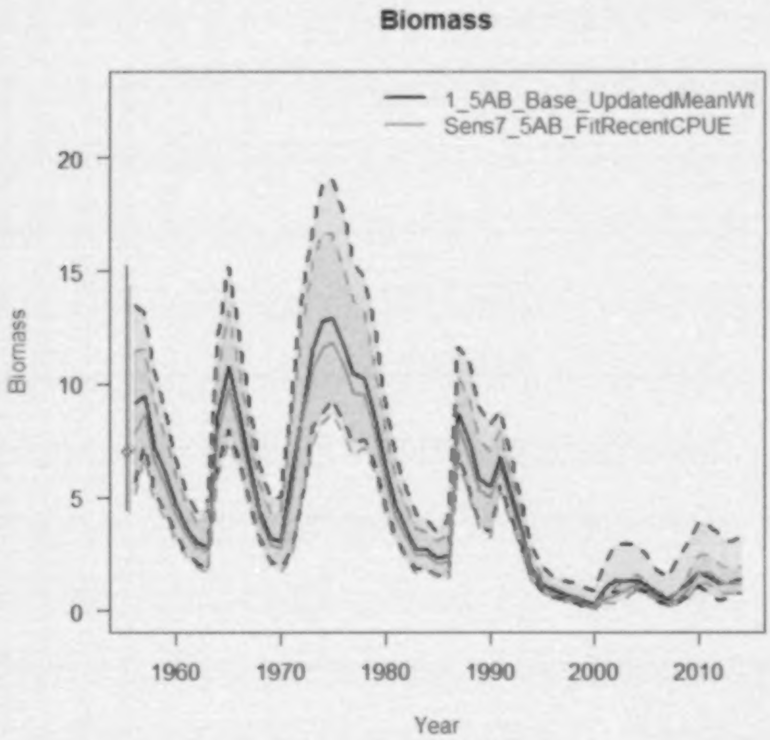


Figure 52. Posterior estimates of biomass (thousand t) with 95% credibility intervals for the ***Area 5AB*** *Base Case model (black) and test of sensitivity to the addition of the commercial CPUE data from 1996-2012. Median posterior estimates of B_0 are shown as points (with 95% credibility interval as error bars).*

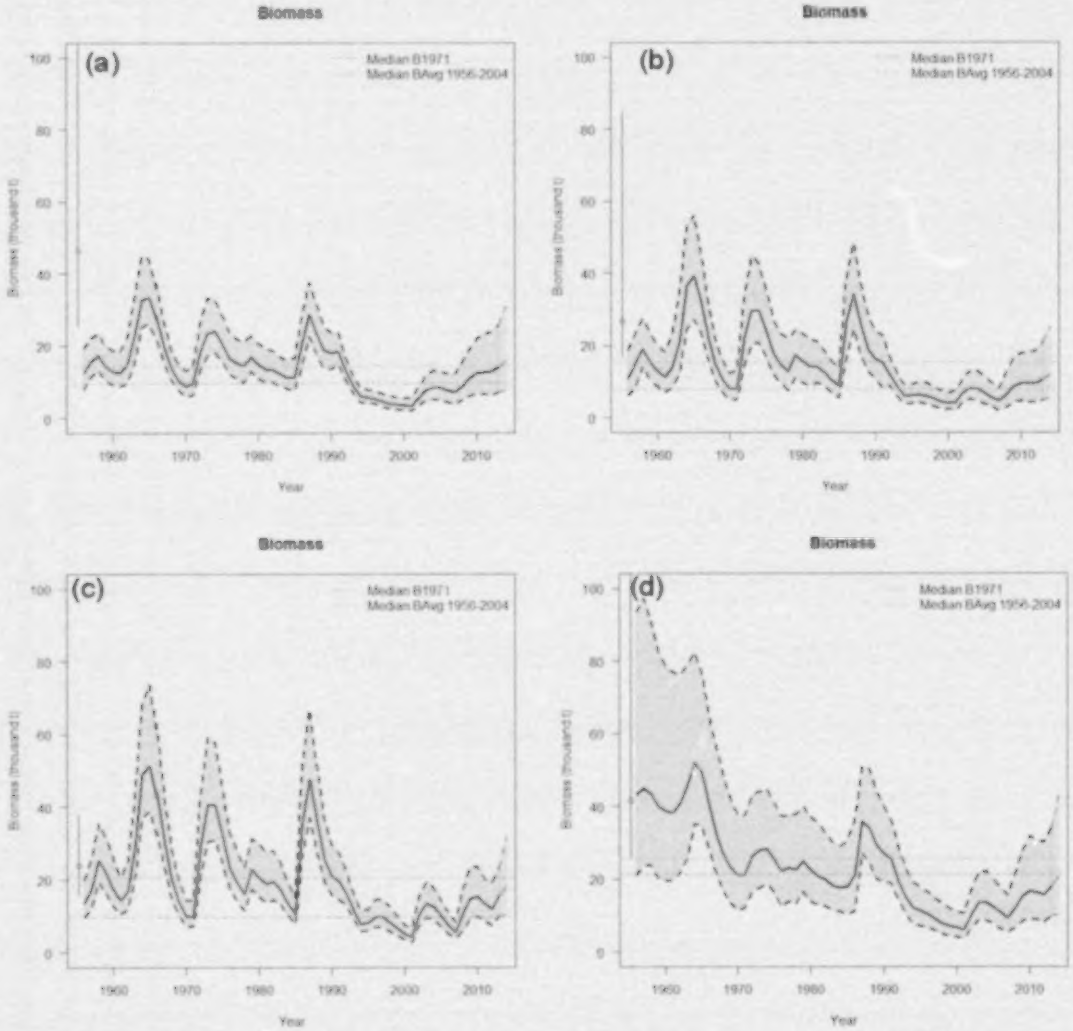


Figure 53. The four sensitivity scenarios used in the model-averaged decision table along with the Base Case model for ***Area 5CD*** *(Table 28): (a) Prior probability distribution for* $\ln(M) = N\sim(0.4,0.2)$*; (b)* $\sigma_w = 0.4$*; (c)* $\sigma_O = 0.15$*; and (d) the model is not fit to the commercial CPUE data. Models (a) – (d) were discussed more fully in the Sensitivity Analyses section.*

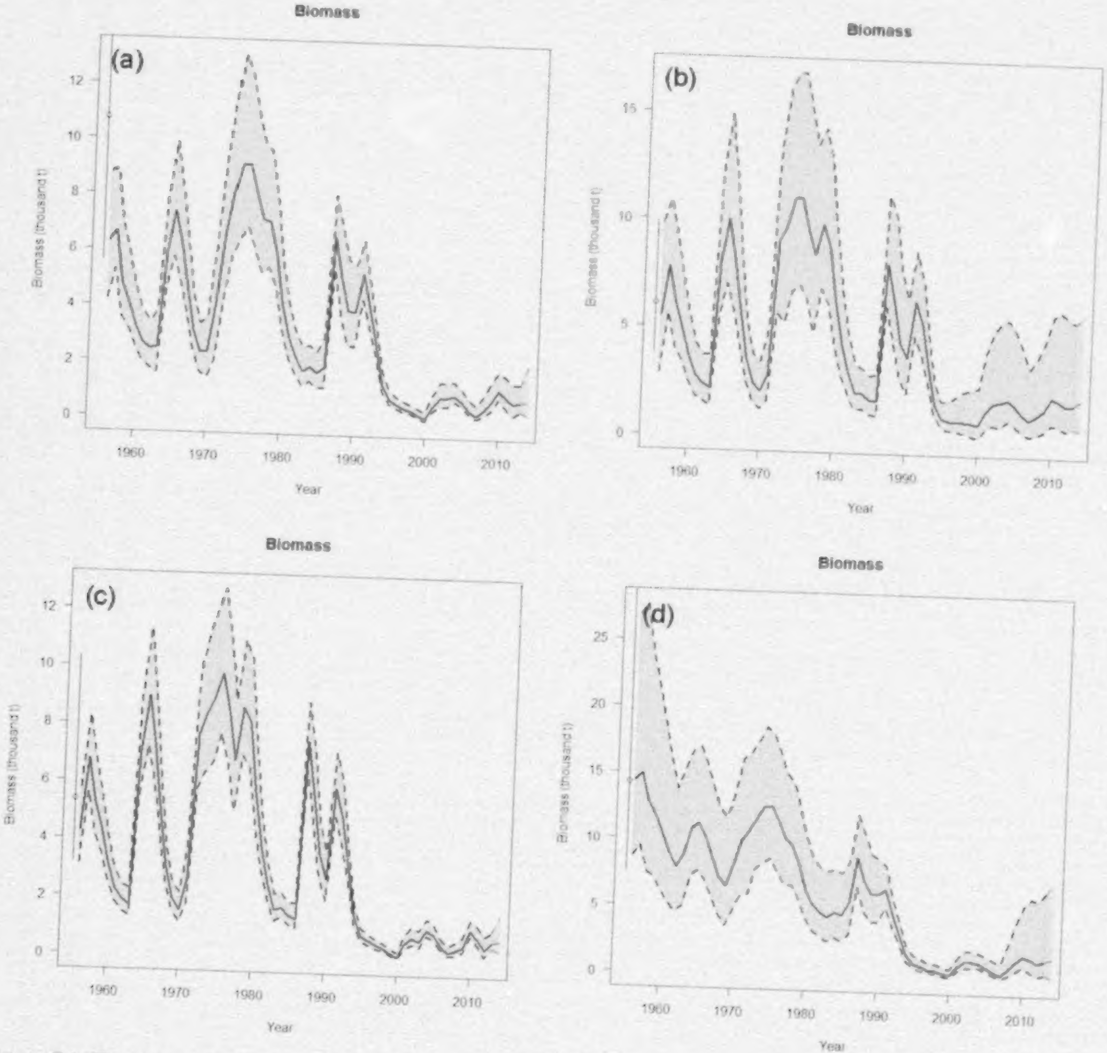


Figure 54. The four scenarios used in the model-averaged decision table along with the Base Case model for ***Area 5AB*** *(Table 29): (a) Prior probability distribution for ln(M) = N~(0.4,0.2); (b) $\sigma_W = 0.4$; (c) $\sigma_O = 0.15$; and (d) the model is not fit well to the commercial CPUE data (using the conditional MPD estimate of $\sigma_{j,i}$). Models (a) – (d) were discussed more fully in the Sensitivity Analyses section. Note different scales.*

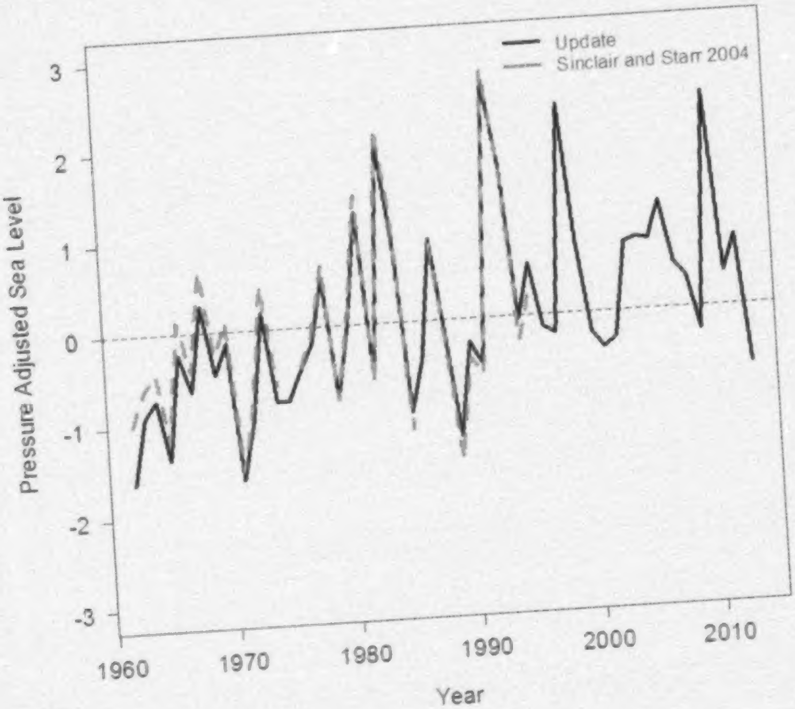


Figure 55. Air pressure adjusted sea level anomalies from Prince Rupert, for the years 1956-2013 (not used in this assessment). Calculated from hourly sea level height from Prince Rupert Harbour and sea level air pressure from Prince Rupert. Source: Environment Canada.

APPENDIX A: BRIDGING ANALYSIS

A bridging analysis provides a means of documenting the transition from the approach used by Sinclair and Starr (2005), and aids in understanding the underlying causes of changes to the stock reconstruction and estimates of key parameters. We present a bridging analysis for the Hecate Strait fishery only, because the Queen Charlotte Sound stock has not been successfully assessed in the recent past. For brevity, we do not present the full suite of sensitivity analyses that were explored but list key steps leading up to development of the candidate Base Case models (Table A1).

For all bridging steps, joint posterior distributions were numerically approximated using the Markov Chain Monte Carlo method implemented in AD Model Builder (Fournier et al. 2012). Posterior samples were drawn systematically every 2,500 iterations from a chain of length five million, resulting in 2,000 posterior samples with the first 1,000 samples removed to allow for burn-in.

Table A1. Description of bridging steps. Indices of Abundance codes: AS = Hecate Strait Multispecies Assemblage Survey; MS = Pacific Cod Monitoring Survey; CPUE = commercial catch per unit effort data (Appendix B) for years 1956-1995; SS = Hecate Strait Synoptic Survey. Steps indicated with a and b alternatives utliized alternative prior probability distributions for ln(M) as described in the text.

Bridging Step	Model	Terminal year	Driving data	Description	Fit to indices of abundance
A1	DD	2005	Effort	Parameters fixed at 2005 values	AS, MS
A2a,b	DD	2005	Effort	All parameters estimated	AS, MS
A3a,b	DD	2013	Effort	As A3, data streams updated to 2013	AS, MS
A4	DD	2013	Effort	As A4, Sensitivity to σ_C	AS, MS
B1a,b	DD	2013	Catch	Estimate ln(F_t)	AS, SS, CPUE
B2	DD	2013	Catch	As B1a, $\sigma_O = 0.1$	AS, SS, CPUE
B3	DD	2013	Catch	As B1a, $\sigma_O = 0.5$	AS, SS, CPUE

STEP A1: RECONSTRUCTION OF PREVIOUS EFFORT-DRIVEN ASSESSMENT WITH FIXED PARAMETERS

The first step in the bridging analysis is to reproduce the results of the previous assessment using the current model (Tables 8-11), with parameters fixed at the values used in 2005 (Table A2). The purpose of this step was to verify that the current model was coded consistently with the previous model.

The model in Step A1 was conditioned on the same effort time series used in 2005 and fit to the historical total catches published in Sinclair and Starr (2005), with the parameter q_c fixed (Table A2). Sinclair and Starr (2005) used an additive iterative reweighting approach to weight the Assemblage Survey and Pacific Cod Monitoring Survey data (Sinclair and Starr 2005). To emulate their observation error terms in the current model, we set φ^{-2} and ρ to give $\sigma_R = 0.4$ and $\sigma_O = 1.0$, then set the weighting term c_j for each index as $c_j = \left(\sqrt{CV_{i,j}^{\,2} + w_j^{\,2}}\right)^{-1}$, where $w_j = 0.68$ and 0.0 for the Assemblage Survey and Pacific Cod Monitoring Survey, respectively, and annual CV's are given in Table A3. This approach resulted in annual values of $\sigma_{i,j}$ identical to those used in Sinclair and Starr (2005).

Figure A1a shows estimates of biomass and recruits from the fixed parameter delay difference model compared with estimates published by Sinclair and Starr (2005; their Table 15, Fixed *h* run). The similarity of the reconstructed biomass and recruitment times series indicates that current models are coded consistently with the model of Sinclair and Starr (2005) and produces consistent results under the same assumptions.

Slight variations between the reconstructions obtained from the current model and the 2005 model are the result of slight differences in the fit to the catch data. In general, the current model tended to fit the catch data more precisely than the 2005 model (Fig. B2).

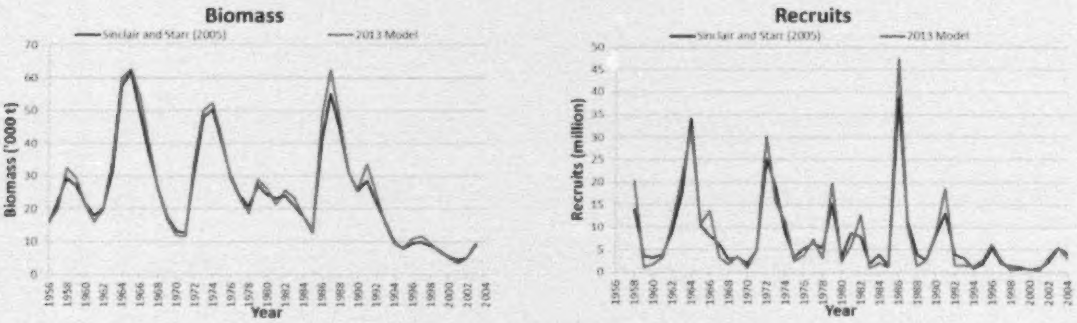


Figure A1. MPD estimates of Biomass and Recruits from bridging Step A1 (red line), compared with results published in Sinclair and Starr (2005) (black line).

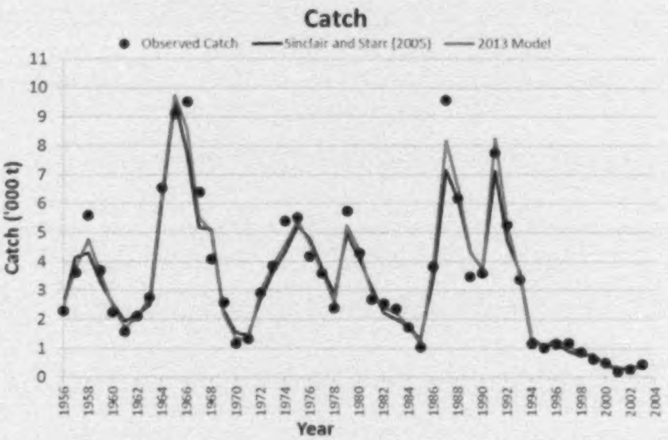


Figure A2. MPD estimates of Catch from bridging Step A1 (red line), compared with results published in Sinclair and Starr (2005) (black line).

Table A2. Fixed parameters and prior probability distributions used in the first steps of the bridging analyses. Superscripts on probability distributions for ln(M) indicate alternative bridging steps as listed in Table A1. Subscripts on Ln(q) parameters indicate: A = Hecate Strait Multispecies Assemblage Survey; S = Hecate Strait Synoptic Survey; and CPUE = commercial CPUE data for the years 1956-1995. σ_R and σ_O were derived from φ^{-2} and ρ using Eq. T11.1 and T11.2.

Parameter	**Step: A1**	**A2**	**A3**	**A4**
Ln(R_0)	8.487	*Uniform*(1,15)	*Uniform*(1,15)	*Uniform*(1,15)
Ln(R_{Avg})	*Uniform*(1,12)	*Uniform*(1,12)	*Uniform*(1,12)	*Uniform*(1,12)
Ln(R_{Avg_init})	*Uniform*(1,12)	*Uniform*(1,12)	*Uniform*(1,12)	*Uniform*(1,12)
Steepness, *h*	0.75	*Beta*(5.833, 2.5)	*Beta*(5.833, 2.5)	*Beta*(5.833, 2.5)
Ln(M)	-0.5175146	*Norm*(-0.518, 0.1)[a] *Norm*(-0.916, 0.1)[b]	*Norm*(-0.518, 0.1)[a] *Norm*(-0.916, 0.1)[b]	*Norm*(-0.518,0.1)
q_C	2.192e-5	*Lnnorm*(2.e-5,0.1)	*Lnnorm*(2.e-5,0.1)	NA
***Ln*(q_A)**	-5.84719	*Uniform*(-16, 0)	*Norm*(0,0.5)	*Norm*(0, 0.5)
***Ln*(q_M)**	-3.62684	*Uniform*(-16, 0)	*NA*	NA
***Ln*(q_S)**	NA	NA	*Norm*(0, 0.5)	*Norm*(0, 0.5)
σ_C	0.1	0.1	0.1	0.025
σ_W	0.2	0.2	0.2	0.2
Variance parameters				
φ^{-2}	0.86207	0.609576	1.423488	1.423488
ρ	0.86207	0.609576	0.088968	0.088968
σ_R	0.4	0.8	0.8	0.8
σ_O	1.0	1.0	0.25	0.25

Step A2: Effort-driven model with estimated parameters

As in the previous step, Step A2 applied the delay difference model conditioned on the qualified effort data series from Sinclair and Starr (2005). Parameters of the model were estimated, with broad prior probability distributions shown in Table A2. Wherever possible, uniform distributions were used. Productivity parameters *M* and *h* required informative priors to prevent implausibly high estimates, particularly for *M*.

Given the importance of estimates of *M* to determining population scale, two alternative prior probability distributions for ln(*M*) were considered: (i) in Step A2a the prior was a normal distribution with mean ln(0.5) and standard deviation (SD) = 0.1; and (ii) in Step A2b the prior was a normal distribution with mean ln(0.4) and SD = 0.1 (Table A2). The means of these two distributions were intended to be based on MPD values from the Fixed Steepness (*M* = 0.596) and Estimated Steepness (*M* = 0.400) alternative runs from Sinclair and Starr (2005).

However, we achieved very poor model convergence with a prior probability distribution centred on ln(0.596) and chose ln(0.5) for our "higher *M*" scenario.

Variance parameters were fixed as for the previous step, with the exception that values were chosen to give $\sigma_R = 0.8$ and $\sigma_O = 1.0$ (Table A2). Given the apparent large variability in recruitment for this stock (Figure A1), a higher value of σ_R was considered more appropriate for the current assessment. Sensitivity to this assumption was tested for the Base Case model (see main body of this document).

Median estimates of biomass and recruits were lower in Step A2a than for Step A1, although the posterior interval contained the median estimates from Step A1 (Figure A3). The MPD estimate of *M* was 0.523 y^{-1}, and the MPD estimate of steepness (*h*) was 0.603, i.e., both productivity parameters were estimated to be lower than the fixed values used in Step A1 (Table A2). In Step A2b, the median estimates of biomass and recruits were lower than for Steps A1 and Step B1a (Figure A3). The MPD estimate of *M* was 0.439 y^{-1}, and the MPD estimate of *h* was 0.606. The distribution of posterior estimates of ln(*M*) was very close to the prior distribution in Step A2a (Figure A4a). Posterior estimates of ln(*M*) tended to be greater than prior values in Step A2b, but were lower than posterior estimates in Step A2a (Figure A4b).

These bridging steps illustrate that the estimated scale of the population size for this stock in this model formulation is highly dependent on assumptions about natural mortality, whether fixed or estimated with a prior probability distribution. We note that the biomass and recruitment trajectories for the early part of the time series are almost identical among the three steps and differ only in scale.

Table A3. Annual indices of abundance from the Hecate Strait Assemblage Survey and Pacific Cod Monitoring Survey, with annual $CV_{j,t}$ for index j in year t.

Assemblage	**Index**	**$CV_{j,t}$**
1984	27	0.340
1987	100	0.370
1989	105	0.430
1991	25	0.300
1993	29	0.260
1995	36	0.480
1996	29	0.390
1998	101	0.520
2000	12	0.230
2002	56	0.300
2003	26	0.220
Monitoring	**Index**	**$CV_{j,t}$**
2002	104.5	0.219
2003	302.5	0.236
2004	327.8	0.161

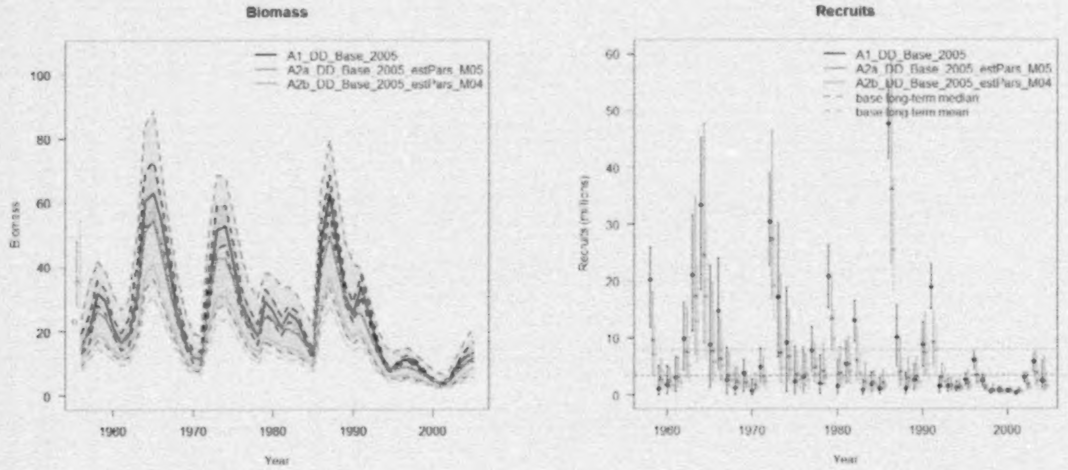


Figure A3. Median posterior estimates (solid lines) and 95% credibility interval (shaded region) of biomass (thousand t); and Recruits from bridging Steps A1, A2a and A2b. Median B_0 (and 95% credibility interval) is shown as an open circle (with error bars).

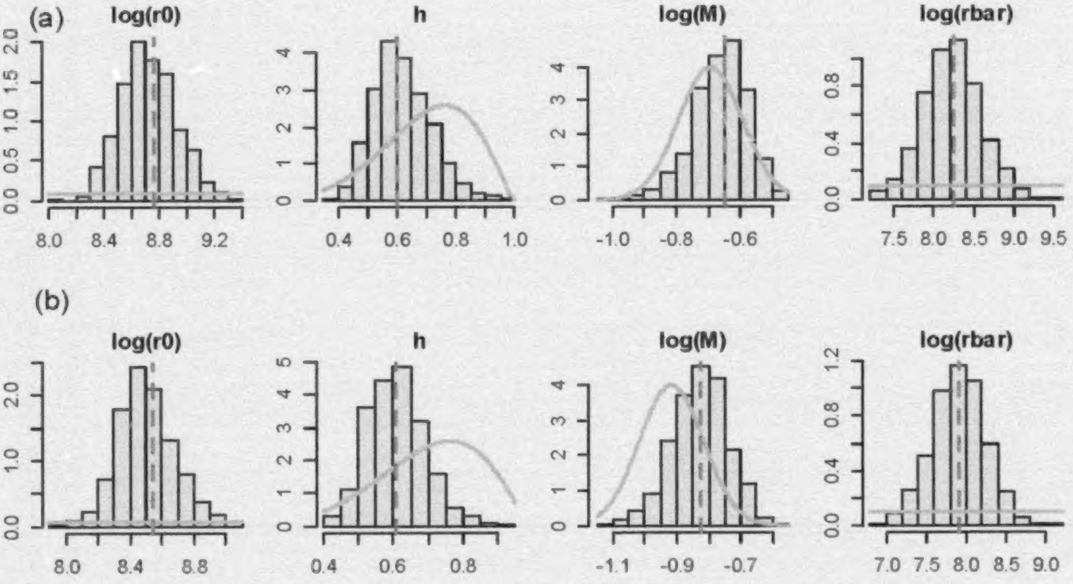


Figure A4. Posterior estimates (bars) of model parameters R_0, steepness (h), ln(M) and ln(R_{Avg}) for: (a) bridging Step A2a and (b) bridging Step A2b. Prior probability distributions are shown as green lines.

Steps A3a and A3b: Updating data streams

The next bridging step is to update the data streams to 2013.

Estimates of historical catch, survey indices, commercial CPUE, and effort were updated in 2013, as described in the Data section in the main body of this document. Given the availability of swept area estimates of biomass from the biennial Hecate Strait Synpotic Survey, we elected to drop the Pacific Cod Monitoring Survey since it overlapped in time with the Hecate Strait Assemblage and Synoptic surveys and only had three data points (Figure 8). We also replaced the index values for the Hecate Strait Assemblage Survey with swept area estimates (see Data section and Table A3). We changed the prior on $\ln(q_j)$ for this survey to a weakly informative normal prior centred on ln(1.0) with SD = 0.5 (Table A2).

Given the new survey index data in this step, it was no longer appropriate to fix the observation error parameters to the values used by Sinclair and Starr (2005). In this step, we set φ^{-2} and ρ to give $\sigma_R = 0.8$ and $\sigma_O = 0.25$ (Table A2). We did not apply any additional weighting parameters and simply set $c_j = CV_{i,j}^{-1}$ (Eq. T11.3 – T11.4), where annual CVs are given in Table A3. As in the previous step A2, the model was run with two alternative prior probability distributions for $\ln(M)$, centred on 0.5 y^{-1} (Step A3a) and 0.4 y^{-1} (Step A3b).

Trends in biomass and recruitment for Steps A3a and A3b were very similar to those in the previous steps (Figure A5). Both models predicted the stock to be continuing on an increasing trajectory beginning in the early 2000s.

Table A3. Annual indices of abundance from the Hecate Strait Assemblage Survey and Hecate Strait Synoptic Survey used for bridging step A4, showing annual $CV_{j,t}$ for index j in year t.

Assemblage	**Index**	**$CV_{j,t}$**
1984	1142.4	0.3031
1987	3875.7	0.3498
1989	4102.8	0.4254
1991	1031.8	0.2977
1993	1255.6	0.2396
1995	1419.8	0.4609
1996	1159.6	0.3739
1998	4253.0	0.5095
2000	436.1	0.1991
2002	2025.9	0.2704
2003	1288.7	0.2088
Synoptic	**Index**	**$CV_{j,t}$**
2003	1940.7	0.2341
2005	585.5	0.2076
2007	2497.6	0.4416
2011	1873.8	0.2607
2013	2351.2	0.2432

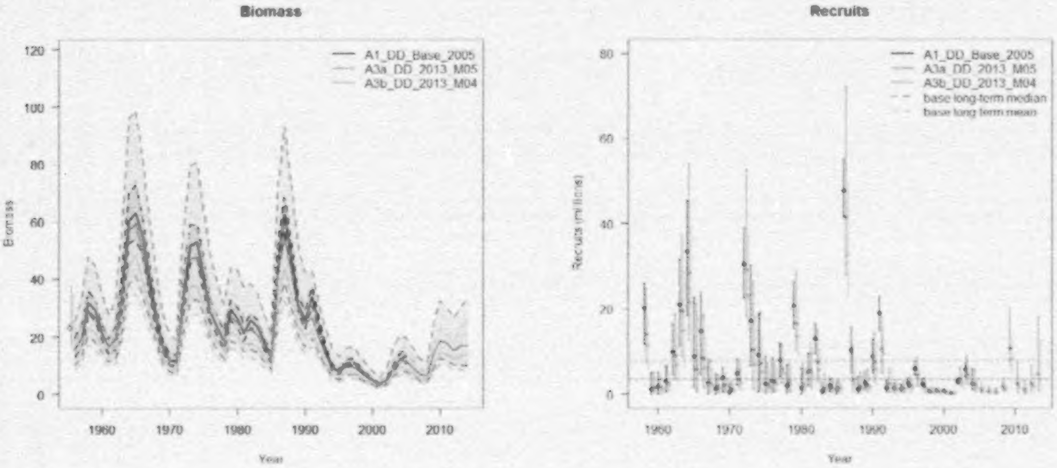


Figure A5. Median posterior estimates (solid lines) and 95% credibility interval (shaded region) of biomass (thousand t); and Recruits from bridging Steps A1, A3a and A3b. Median B_0 (and 95% credibility interval) is shown as an open circle (with error bars).

Step A4: Sensitivity to σ_C

While the results shown in Figure A4 are consistent with previous assessments, we note that all model Steps A1-A3 failed to fit to the 1958, 1987 and 1991 peaks in catch (e.g., Figure A6a). The fixed standard deviation in catch residuals σ_C determines how well the predicted catches fit the observed catch data (Eq. T11.10). In Steps A1-A3, σ_C had been set to 0.1, as in Sinclair and Starr (2005), resulting in the poor fits to catch peaks seen in Figure A6a and in their assessment. In Step A4, σ_C was set to 0.025 to force the predicted catches to closely fit the observed data (Figure A6b).

In this step, it was not possible to obtain plausible estimates of M. All posterior estimates of M were greater than 0.99 y^{-1}. For this step, therefore, M was fixed at 0.596 y^{-1}. The effect of forcing the model to fit to the peaks in the catch data was to scale the estimated biomass downward (Figure A7), while more than doubling the estimate of the parameter that scales the effort data to fishing mortality, q_c. The MPD estimate of q_c was 1.87e-5 in Step A3a compared to 7.50e-5 in Step A4. In summary, forcing the model to fit to the catch data, while fixing M to be less than 0.6 y^{-1}, forced the model to estimate higher catchability in order to explain the peak catches in 1958, 1987 and 1991. Overall biomass was therefore estimated to be much lower. The only other way the model could explain the peak catches was with a highly productive stock with implausibly high natural mortality (i.e., ~ 1.0 y^{-1}).

Estimates of the posterior probability distributions showed poor convergence for catchability parameters. The model also produced worse fits to the mean weight data, estimating mean weights to be around half of observed values (Figure A7).

We note that estimates of biomass, recruits and catch follow almost identical time-series trajectories over all bridging steps examined so far (see also Figure 7). There are differences in scale but not relative trends. A pairs plot of parameter estimates from Step A3a shows an almost linear positive relationship between q_c and the two survey catchability parameters, q_1

and q_2; as well as strong confounding among other parameters (Figure A8). The strong correlations among parameters shown in Figure A8 were typical of all bridging steps so far.

Linear correlations like those in Figure A8 indicate that the model is over-parameterized, i.e., there are too many parameters relative to the information in the data. In this case, we suggest that the assumption of a single parameter q_c that scales the effort data to fishing mortality for the entire time series introduces a rigidity to the model structure. There was also a strong negative correlation between ln(M) and q_c, q_1 and q_2 (Figure A8). Therefore, when M was fixed in Step A4, and the model was also forced to fit to all of the catch data, the estimate of q_c was forced to be larger, causing the decrease in estimated biomass (Figure A7). The extremely narrow posterior interval for the biomass estimates also suggests an inflexible model configuration when the model is forced to fit to the catches.

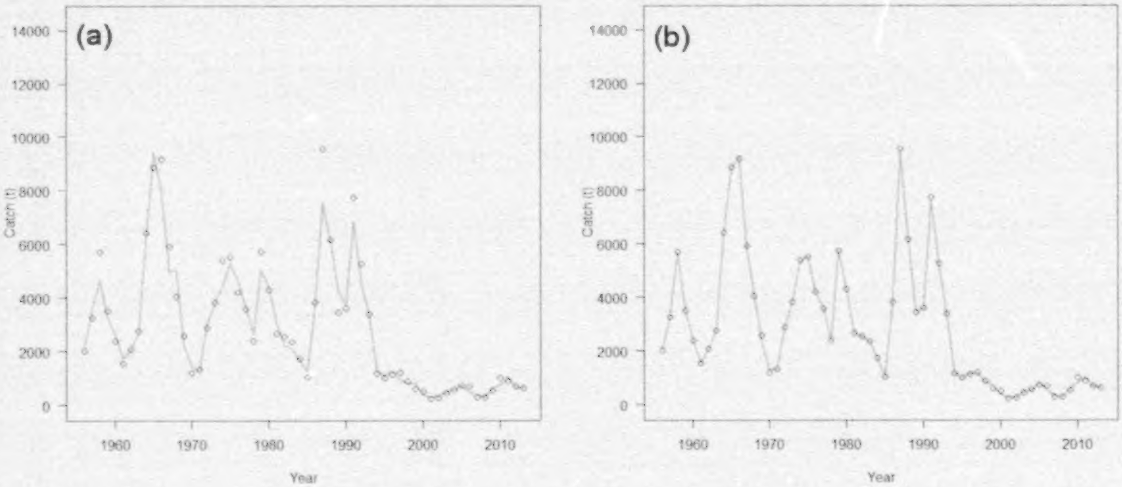


Figure A6. MPD estimates of annual catch, compared with observed values from: (a) bridging Step A3a; and (b) bridging Step A4. Observed values are shown as points with predicted values as lines.

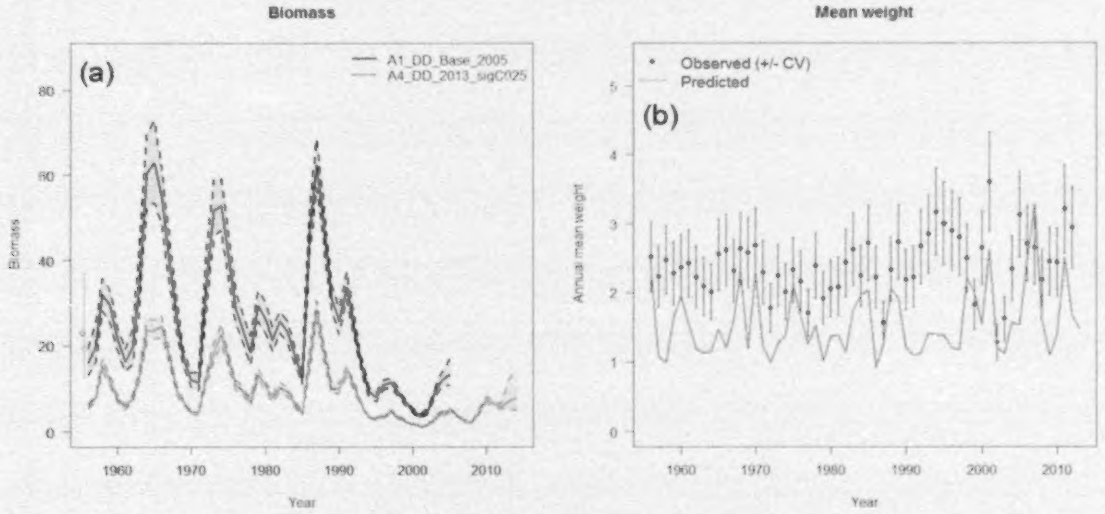


Figure A7. (a) Posterior estimates (median and 95% credibility interval of biomass (thousand t); and (b) MPD fit to the mean weight data for bridging Step A4, where predicted mean weights are shown as a red line and observations are shown as points. Error bars on mean weight observations represent the fixed CV (based on σ_W =0.2). Median B_0 (and 95% credibility interval) is shown as an open circle (with error bars).

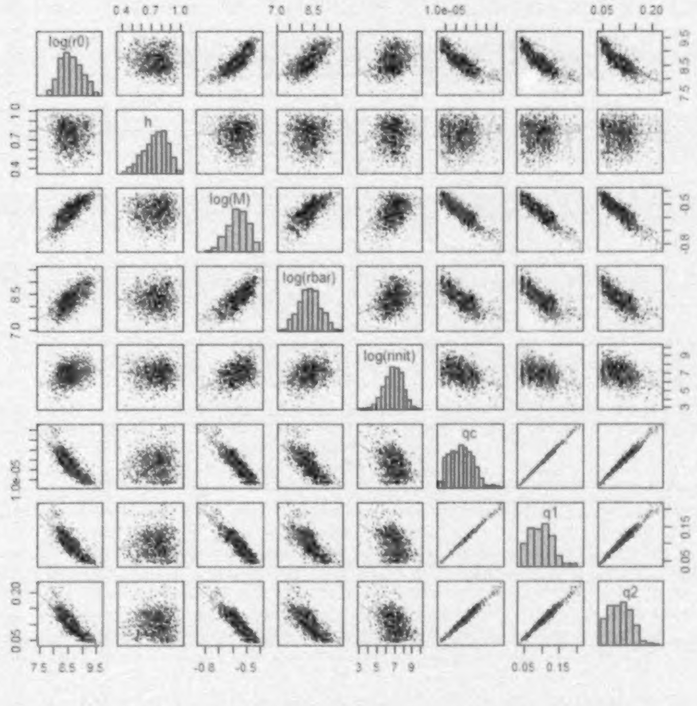


Figure A8. Correlations between posterior parameter estimates from bridging Step A3a. q_1 = Hecate Strait Assemblage Survey; q_2 = Hecate Strait Pacific Cod Monitoring Survey; and q_3 = commercial CPUE data from 1956-1995 for Hecate Strait

Steps B1a and B1b: Catch-driven model

In this Step, we apply an alternative model configuration that removes the reliance of fishing mortality on effort data while still allowing the commercial CPUE data to be admitted into the objective function. Essentially, the CPUE data are used as a third index of abundance, where index points are assumed to be observed with error.

The model in this configuration is fully documented in Tables 8-11, and is described in the main body of this document. Predicted catches are constrained to closely fit observed catches using Eq T11.10 in the objective function, where log residuals are assumed to be normally distributed and σ_C is fixed at 0.05. Note that this can be achieved with a higher value of σ_C than in the previous configuration because fishing mortality is independent of the fixed time series of effort data.

Annual commercial CPUE data are available for the years 1956-2012 (Appendix B). We used Analysis D, the series based on catch and effort data from key Pacific Cod fishing localities (Appendix B). This choice was based on the assumption that these data are most likely to be representative of abundance, and was also made for consistency with Sinclair and Starr (2005). The series was split at 1995, the year before 100% at-sea observer coverage was introduced into the bottom trawl fishery.

Given the availability of fishery-independent survey data post-1995, and the possibility that many vessels have been actively avoiding known fishing areas for Pacific Cod since smaller quotas were introduced in 2001, we did not include the post-1995 commercial CPUE data in the analysis. Therefore, three indices of abundance were available as inputs to the model: (1) the Hecate Strait Multispecies Assemblage Survey; (2) the Hecate Strait Synoptic Survey; and (3) the 1956-1995 commercial trawl catch per unit effort series, $\mathrm{CPUE}_{1956\text{-}1995}$. The period covered by the two fishery independent surveys was summarized in Table A3.

The first steps in implementing the model in this configuration used the same priors and fixed variance parameters as Steps A3a and A3b (Table A4). As for previous steps, two alternative priors for ln(*M*) were tested: normal distributions centred on ln(0.5) and ln(0.4), with SD = 0.1. The parameter σ_C was set to 0.05. Annual CVs were not available for the commercial CPUE data, which were obtained from a simple arithmetic approach described in Appendix B. A CV of 0.25 was assumed for each observation in the commercial CPUE data. Sensitivity to this value is analyzed in a later section.

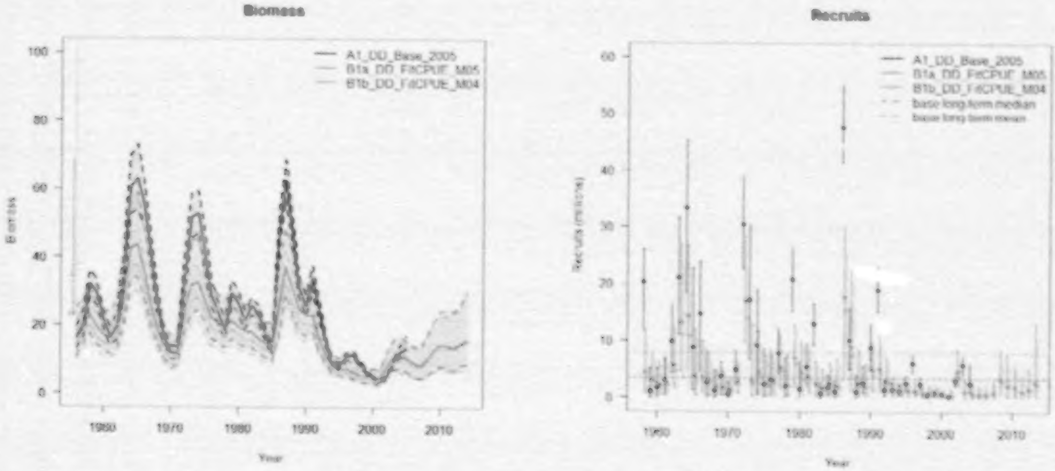


Figure A9. Posterior estimates (median and 95% C.I.) of biomass (thousand t); and Recruits from bridging Steps A1, B1a and B1b. Median B_0 (and 95% credibility interval) is shown as an open circle (with error bars).

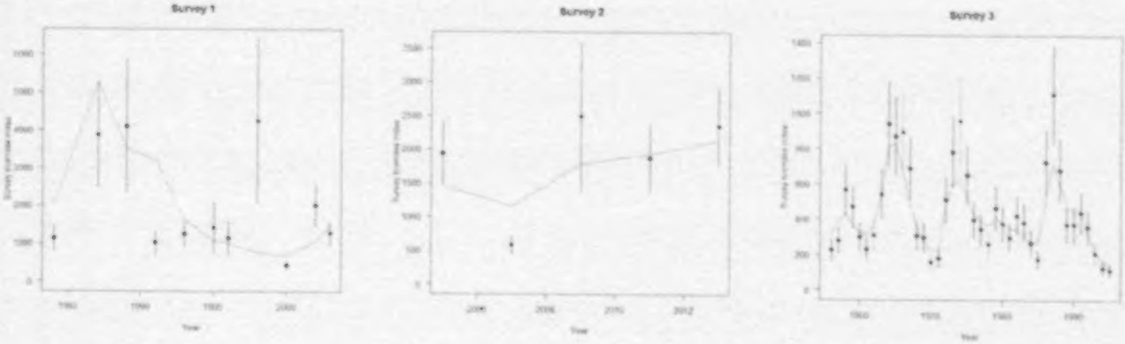


Figure A10. MPD fits to indices from the Hecate Strait Assemblage Survey (L), the Hecate Strait Synoptic Survey (C), and the commercial CPUE series (R) for bridging Step B1a. Fits were similar for Step B1b.

Table A4. Fixed parameters and prior probability distributions used in the first steps of the bridging analyses. Superscripts on distributions for ln(M) indicate alternative bridging steps as listed in Table A1. Subscripts on Ln(q) parameters indicate: A = Hecate Strait Multispecies Assemblage Survey; S = Hecate Strait Synoptic Survey; and CPUE = commercial CPUE data for the years 1956-1995. Note that σ_R and σ_O were derived from φ^{-2} and ρ using Eq. T11.1 and T11.2.

Parameter	Step: B1	B2	B3
Ln(R_0)	*Uniform*(1,15)	*Uniform*(1,15)	*Uniform*(1,15)
Ln(R_{Avg})	*Uniform*(1,12)	*Uniform*(1,12)	*Uniform*(1,12)
Ln(R_{Avg_init})	*Uniform*(1,12)	*Uniform*(1,12)	*Uniform*(1,12)
Steepness, *h*	*Beta*(5.833, 2.5)	*Beta*(5.833, 2.5)	*Beta*(5.833, 2.5)
Ln(M)	*Norm*(-0.693, 0.1)[a] *Norm*(-0.916, 0.1)[b]	*Norm*(-0.693, 0.1)	*Norm*(-0.693, 0.1)
Ln(q_A)	*Norm*(0,0.5)	*Norm*(0,0.5)	*Norm*(0,0.5)
Ln(q_S)	*Norm*(0, 0.5)	*Norm*(0, 0.5)	*Norm*(0, 0.5)
Ln(q_{CPUE})	*Uniform*(-16, 0)	*Uniform*(-16, 0)	*Uniform*(-16, 0)
σ_C	0.05	0.05	0.05
σ_W	0.2	0.2	0.2
	Variance parameters		
φ^{-2}	1.423488	1.538462	1.123596
ρ	0.088968	0.015385	0.280899
σ_R	0.8	0.8	0.8
σ_O	0.25	0.10	0.50

Median estimates of biomass and recruitment in both Steps B1a and Step B1b were lower than in previous steps (Figure A9). In both runs, *M* was estimated to be lower than in previous steps, with MPD estimates of 0.393 y^{-1} and 0.345 y^{-1} for Steps B1a and B1b, respectively.

Predicted indices of abundance followed the general trends of the observations but did not fit the data closely, especially the commercial CPUE data (Figure A10). We suggest that the model estimated lower values of *M* in this configuration because it was not constrained to fit to the highest peaks of the CPUE data, notably in the mid-1970s and in 1987.

Pairs plots of posterior parameter estimates from Step B1b show less confounding between parameters compared to the previous model configuration, particularly between *M* and catchability parameters q_j (Figure A11). The model provided near perfect fits to the catch data and reasonable fits to the mean weight data, although, as in the previous steps, mean weights were under-estimated during the 1990s (Figure A12).

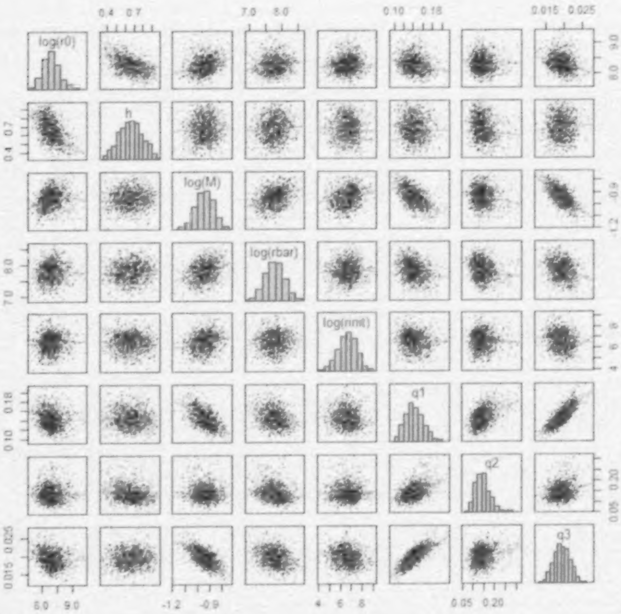


Figure A11. Correlations between posterior parameter estimates from bridging Step B1a. q_1 = Hecate Strait Assemblage Survey; q_2 = Hecate Strait Synoptic Survey; and q_3 = commercial CPUE data from 1956-1995 for Hecate Strait.

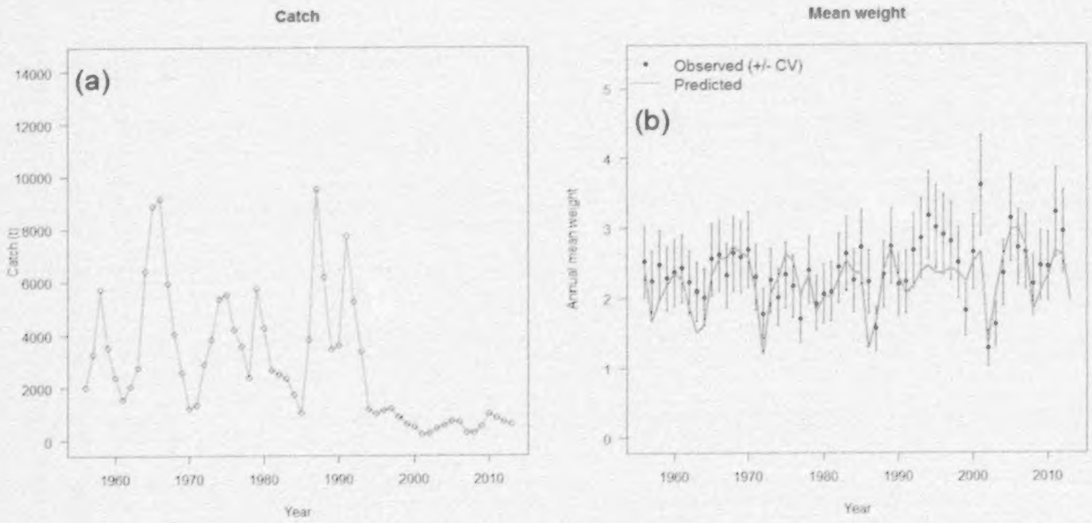


Figure A12. (a) MPD estimates of annual catch, compared with observed values; and (b) MPD fit to the mean weight data from bridging Step B1a, where predicted mean weights are shown as a red line and observations are shown as points. Error bars on mean weight observations represent the fixed CV (based on σ_W =0.2). Observed values are shown as points with predicted values as lines. Results were very similar for Step B1b.

Steps B2 and B3: Sensitivity to fit to commercial CPUE data

Fixed variance parameters can have a large influence on model outcomes. The effect of higher and lower values of overall observation error term σ_O was tested in Steps B2 and B3. Previous steps used values for fixed variance parameters φ^{-2} and ρ to give $\sigma_O = 0.25$ (Eq. T11.1 and T11.2). In a sensitivity analysis to the variance parameters in the previous step, variance parameters were fixed to give $\sigma_O = 0.1$ in Step B2 and, and $\sigma_O = 0.5$ in Step B3 (Table A4). These arbitrary values were intended to test the effect of assuming higher and lower overall variance in the survey observations.

The effect of the prior probability distribution for ln(*M*) has been shown in previous steps and we drop further comparisons in this bridging analysis. Steps B2 and B3 were both run with a prior probability distribution for ln(*M*) with Mean = 0.5 and SD = 0.1 (Table A4).

As expected, setting σ_O to 0.1 in Step B2 resulted in very close fits to the Synoptic Survey and CPUE data (Figure A13), although we note that the model did not fit to peaks in CPUE in 1974 or 1987. Conversely, setting σ_O to 0.5 in Step B3 degraded the fit to all indices of abundance, most notably the commercial CPUE data (Figure A14).

Relaxing the fit to the CPUE data in Step B3 resulted in a slight decrease in estimated biomass in the recent part of the time series, while smoothing out the estimated peaks and troughs in the 1970s and 1980s. The median estimated current biomass and 95% credibility interval was lower than in the other steps shown (Figure A15). The lower estimates of biomass at the recent end of the time series is likely in large part due to the poorer fit to the 2013 Hecate Strait Synoptic Survey observation (Figure A14).

Despite the similarity in recent trajectories resulting from Steps B1a to B3, there were notable differences in estimates of productivity parameters *M* and steepness (*h*). MPD estimates of *M* and *h* were much higher in Step B2 than for the other "B" steps (Table A5). The interpretation is that forcing the model to closely fit the commercial CPUE data by setting $\sigma_O = 0.1$ resulted in the model predicting a far more productive stock to explain the large peaks in biomass and catch. Much larger peaks in recruitment were also estimated in Step B2 (Figure A15).

We also note that the lower estimates of *M* and *h* obtained in Step B1a (due to a lower mean value in the prior probability distribution for ln(*M*)) and in Step B3 (due to relaxing the goodness of fit to the commercial CPUE data) were associated with larger and much more uncertain estimates of B_0 (Table A5; Figures B9 and B15). Therefore, while the biomass trajectories were similar in all cases, especially at the recent end of the time series (Figure A14), MSY-based reference points, which are derived from estimates of *M, h* and B_0 (Table 9), were very different among scenarios (Figure A16).

Table A5 and Figure A16 imply that estimates of MSY-based reference points are in part a function of the goodness of fit to the index of abundance data. Given the inestimability of variance parameters in this assessment, the goodness of fit to the indices of abundance must rely on subjective decisions about the value of σ_O. For this reason, we concur with the conclusions of the 2005 stock assessment authors and review committee that reference points based on the reconstructed history of the stock are preferable to MSY-based reference points for this fishery (Sinclair and Starr 2005; Fargo 2005).

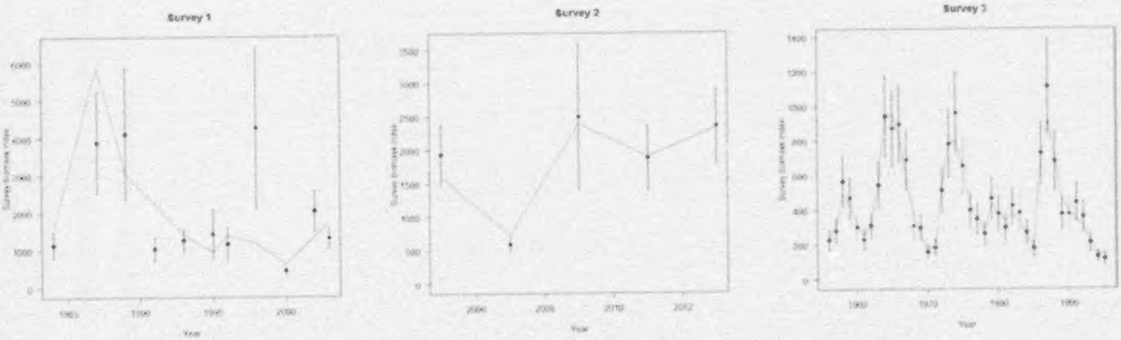


Figure A13. MPD fits to indices of abundance data from: (a) the Hecate Strait Multispecies Assemblage Survey; (b) the Hecate Strait Synoptic Survey; and (c) the commercial CPUE series in bridging Step B2.

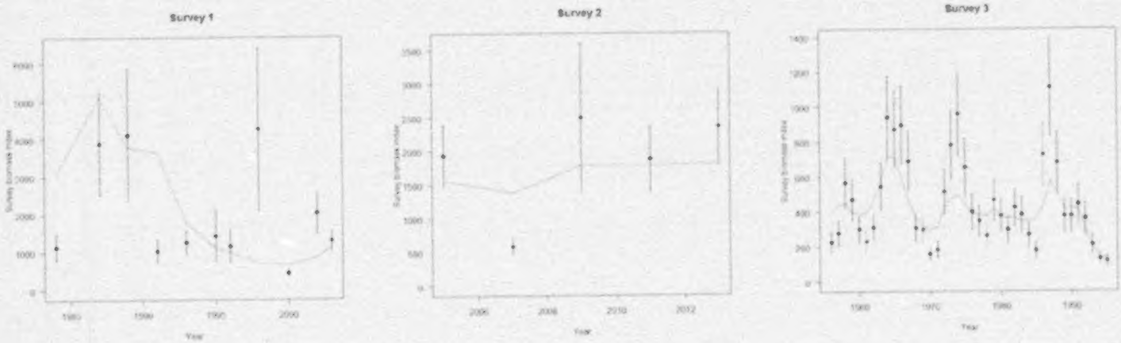


Figure A14. MPD fits to indices of abundance data from: (a) the Hecate Strait Multispecies Assemblage Survey; (b) the Hecate Strait Synoptic Survey; and (c) the commercial CPUE series in bridging Step B3.

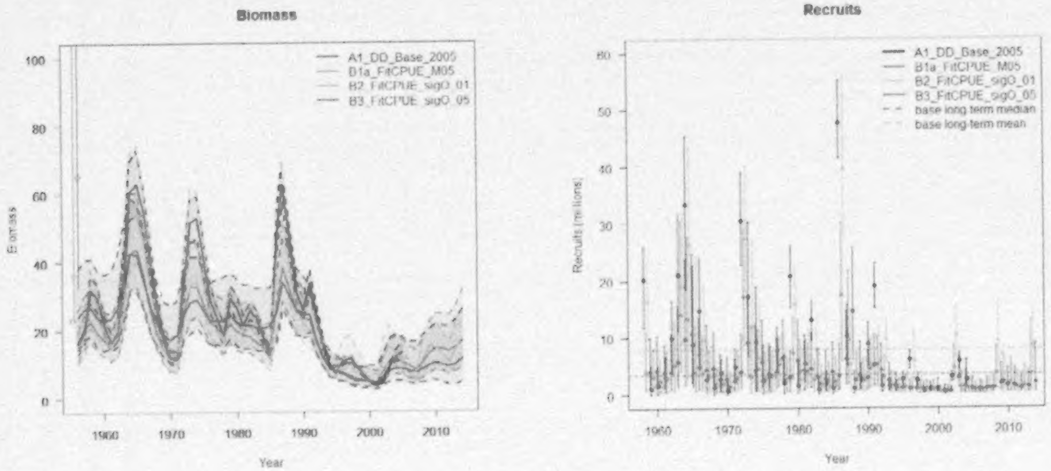


Figure A15. Posterior estimates (median and 95% credibility interval) of biomass (thousand t) and recruits from Steps A1, B1a,B2 and B3. Median B0 (and 95% credibility interval) is shown as an open circle (with error bars).

Table A5. Median (and MPD) estimates of M, steepness and B_0, from bridging steps B1a, B1b, B2 and B3. Differences in estimates of M between Steps B1a and B1b arise from differences in the mean of the prior probability distribution for ln(M), shown in Table A4. Differences in estimates of M and steepness between Steps B2 and B3 arise from differences in the fixed value of the overall observation error term σ_O, which is derived from the fixed parameters φ^{-2} and ρ using Eq. T11.1 and T11.2.

Step	σ_O	M	Steepness	B_0
B1a	0.25	0.392 (0.393)	0.643 (0.663)	36.23 (41.95)
B1b	0.25	0.346 (0.345)	0.649 (0.654)	37.92 (47.42)
B2	0.10	0.546 (0.574)	0.757 (0.786)	21.80 (24.41)
B3	0.50	0.382 (0.375)	0.457 (0.460)	65.30 (90.84)

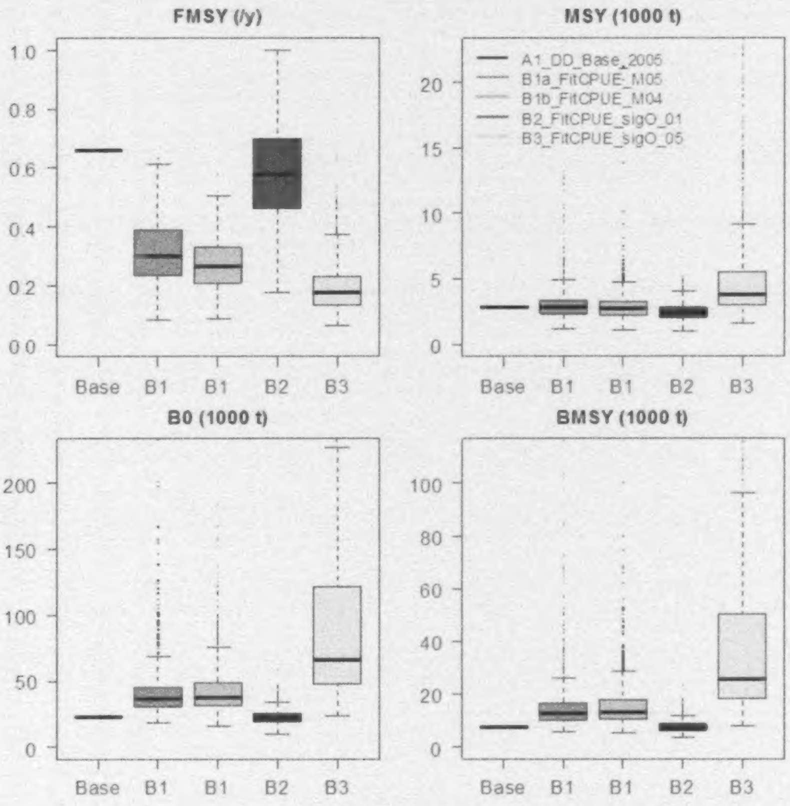


Figure A16. Posterior estimates of equilibrium reference points F_{MSY}, MSY, B_0 and B_{MSY} for Steps A1 (Base), B1a, B1b,B2 and B3..Boxplots show median (horizontal black line), the interquartile range IQR (boxes) and 1.5 IQR (whiskers). Note that most parameters were fixed in the Step A1, giving the narrow interval.

CONCLUSIONS FROM BRIDGING ANALYSES

The key conclusions from this analysis are:

1. The model in its 2005 configuration could not explain peak catches. Natural mortality was estimated to be very high in order to explain large peaks in biomass arising from the assumption of a constant, invariant relationship between fishing mortality and fishing effort throughout the time series.
2. Reconfiguring the model allowed catches to be fit very closely, while relaxing the influence of peaks in the CPUE data on estimates of productivity. Estimates of productivity parameters were influenced by how well the model fit to peaks in the index data.
3. While the biomass trajectories were similar in most model steps, especially at the recent end of the time series (Figure A15), MSY-based reference points were strongly influenced by fixed variance parameters and the prior for natural mortality (Figure A16). For this reason, we concur with the conclusions of the 2005 stock assessment authors and review committee that reference points based on the reconstructed history of the stock are preferable for this stock (Sinclair and Starr 2005; Fargo 2005).

Further sensitivity analyses are presented in the main body of this document.

We suggest the model presented in Step B1a be used as the Base Case model for the Area 5CD stock of Pacific cod. We suggest the same model configuration and parameter settings be used for the Area 5AB stock.

APPENDIX B: ANALYSIS OF CATCH PER UNIT EFFORT DATA: HECATE STRAIT AND QUEEN CHARLOTTE SOUND

METHODS

The criteria used to select data for the calculation of CPUE for Area 5AB (Queen Charlotte Sound) and Area 5CD (Hecate Strait) Pacific Cod are listed in Table B1. The filtering criteria used to select GFCatch data have changed slightly from those used for the 2004 assessment, with the utilization category "bait" being changed from discarded to landed catch.

Catch data are available on a tow-by-tow basis in the PacHarvest and GFFOS databases where each tow has at least two associated depth fields (beginning and end of tow). However, data in the GFCatch database before 1991 are only available in summary form because vessels reported on a "trip" basis and provided "rolled-up" reports of catch for defined "localities" within approximately 10 fathom depth bands (Rutherford 1998). Most records would have two associated depth bands which were interpreted by the algorithm in Table B2. Beginning in January 1991, the data in GFCatch are reported on a tow-by-tow basis and are treated in the same manner as the later data.

All data were summarized into "fishing years" (April 1 – March 31) to provide continuity with previous Pacific Cod assessments.

Four CPUE analyses (defined in Table B3) were performed on the 5AB and 5CD data sets selected using the selection criteria presented in Table B1. These analyses were extensions of the analyses performed for the 2004 assessment. A range of analyses was required because there had been a substantial drop in the Hecate Strait Pacific Cod TAC on 1 April 2001, which altered the behaviour of fishermen and consequently affected the comparability of the later CPUE indices with those from earlier years. Three of the selected analyses attempt to adjust for this effect while the fourth is presented as a continuation with the analysis performed for the 2001 Hecate Strait assessment.

One approach used to correct for changes in effort behaviour was to identify "key localities" where Pacific Cod have been captured throughout the catch history period (Table B4). The areas selected for Hecate Strait were the same as those used in the Hecate Strait Pacific Cod Monitoring survey (Sinclair 2002) while the cumulative catch data were examined to identify similar areas in Queen Charlotte Sound. It appears that locality of catch was not recorded for 5AB (Queen Charlotte Sound) before 1966, while reporting of locality information was more common in 5CD (Hecate Strait) in these early years (Figure B1). Therefore, Analysis "D" for Queen Charlotte Sound (Table B4) uses the catch and effort data from Analysis "A" for all fishing years before 1966/67.

All analyses were performed on total mortalities (landed catch+discards), but this may potentially bias the analyses, given that reliable discard data have only been available since 1996. However, it is important to include the recent discard information to obtain a complete index for this species, given the low TAC for Hecate Strait Pacific Cod beginning in 2001. This approach assumes that discarding of Pacific Cod was minimal before 1996/97.

Catch and effort (either as total hours fished or number of tows) were summed for each analysis by April 1 to March 31 fishing year, beginning in April 1, 1956. Arithmetic and geometric CPUE indices were calculated for each fishing year (j) using the following equations:

Eq .B1 $$\text{arithmetic CPUE}_j = \frac{\sum_{k=1}^{M_j} C_{jk}}{\sum_{k=1}^{M_j} E_{jk}}$$

Eq. B2 $$\text{geometric CPUE}_j = \exp\left[\frac{\sum_{k=1}^{M_j} \ln\left(\frac{C_{jk}}{E_{jk}}\right)}{M_j}\right]$$

where k indexes each fishing event in each data set and M_j is the number of fishing events by fishing year in the data set. Effort (E_{jk}) can be either the number of tows or hours fished and catch (C_{jk}) is in kilograms. Comparisons between index series were made by taking the geometric mean of each series across the same years.

AREA 5CD: HECATE STRAIT

Plots of the CPUE indices, standardised relative to the geometric mean CPUE for each series, do not show much sensitivity to the analysis assumptions when the plots are viewed for all fishing years (Figure B2, Table B5), with the annual variations in CPUE well captured by all of the data preparation assumptions. However, the most recent (2012/13) index value is somewhat higher for the "key locality" series than for the other three series (Figure B3, Table 5).

There is little sensitivity in the 5CD CPUE index to the choice of the effort variable, with both "hours fished" and "tows" giving very similar relative index values (Figure B4). A comparison of CPUE annual indices calculated using an arithmetic mean (Eq .B1) with a geometric mean (Eq. B2) shows relatively little difference between the two series (Figure B5). The strong peak estimated in the mid-1960s is higher for the geometric mean series while the final peak in 2010/11 is lower than for the arithmetic series. There were no differences in the overlapping sections of the 5CD CPUE series between the index values calculated by Sinclair and Starr (2005) and current 5CD Pacific Cod assessments (Figure B6).

AREA 5AB: QUEEN CHARLOTTE SOUND

Plots of the CPUE indices standardised relative to the mean CPUE for the series based on all effort (Analysis A) and the effort only from key localities (Analysis D) are nearly identical, while Analyses B and C show lesser peaks in CPUE for the peak years in the 1970s and the early 1990s (Figure B7, Table B5). The similarity between Analyses A and D should not be surprising because, given the information in Figure B1, where almost the entire Pacific Cod catch in 5AB comes from these seven localities. The CPUE indices for Analysis A are slightly higher than for those in Analysis D for 2001/02 and 2002/03, possibly suggesting some movement away from traditional Pacific Cod fishing grounds in those years (Figure B8, Table B5). However, this difference disappears in the following years.

As seen for 5CD, there is little sensitivity in the 5AB CPUE series to the choice of the effort variable, with both "hours fished" and "tows" giving very similar relative index values (Figure B9). A comparison of CPUE annual indices calculated using an arithmetic mean (Eq. B1) with a geometric mean (Eq. B2) shows a similarity in patterns between the two series (Figure B10). However, most of the CPUE peaks are higher for the arithmetic mean series than for the geometric mean series, including the final peak years in 2010/11 and 2011/12. There were no differences in the overlapping sections of the 5AB CPUE series between the index values calculated by Sinclair and Starr (2005) and current 5AB Pacific Cod assessments (Figure B11).

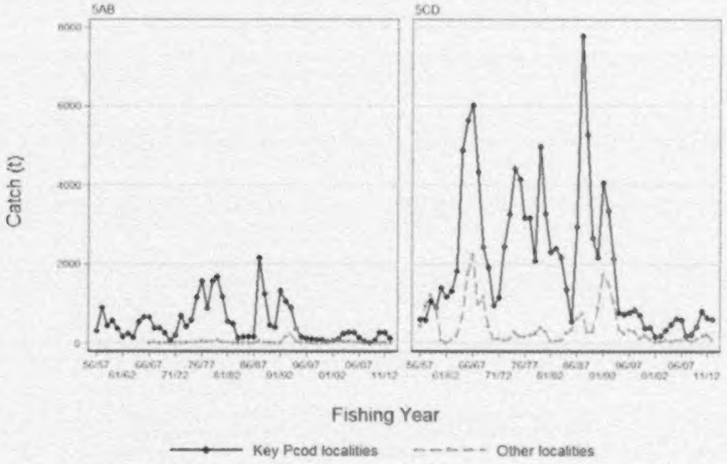


Figure B1. Plots of the catch of Pacific Cod in "key localities" identified in Table B4 and the catch in the remaining localities (including the designation "unknown") for 5AB and 5CD.

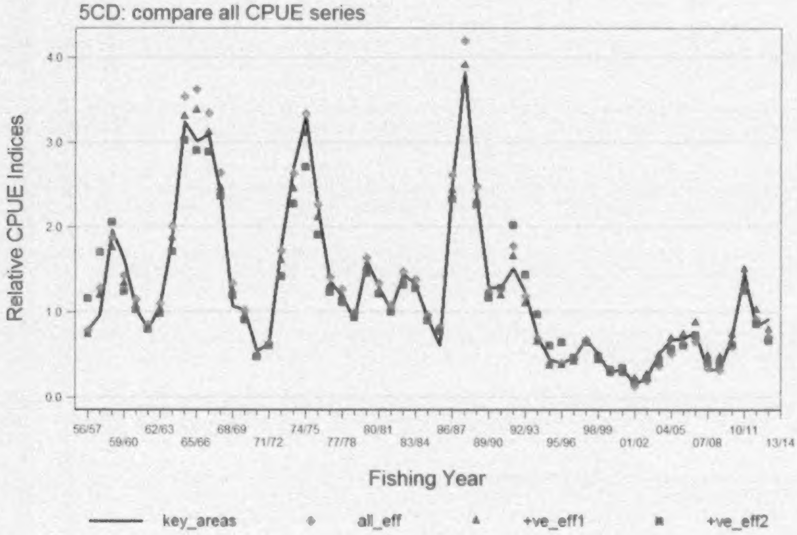


Figure B2. Plot of four arithmetic CPUE indices (Eq. B1) for Hecate St. (5CD) Pacific Cod using hours fished as the measure of effort: key_areas=all qualified effort in key Pcod localities (Figure B1); all_eff=all qualified effort; +ve_eff1=all effort <=2000/01 & positive effort>2000/01; +ve_eff2=effort with positive catches only. See Table B4 for a complete description of each analysis. The geometric mean of each series has been standardised to equal 1.0.

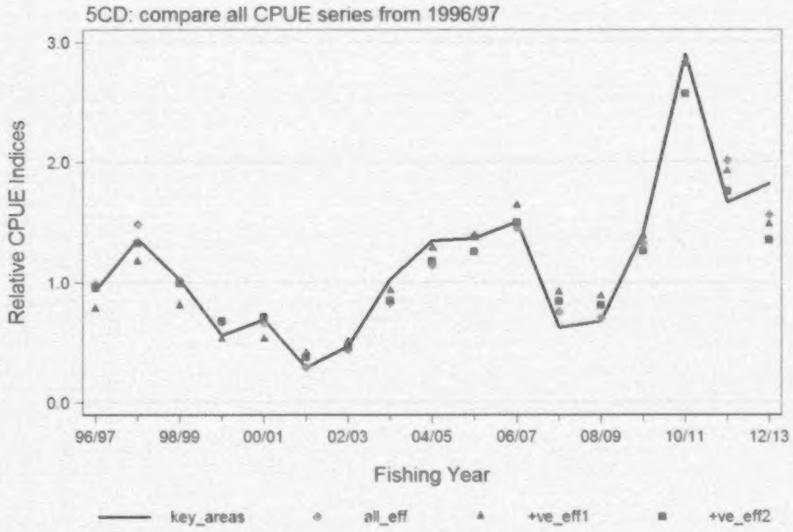


Figure B3. Plot of four arithmetic CPUE (Eq. B1) index series for 5CD (Hecate Strait) Pacific Cod from 1996/97 to 2012/13 using hours fished as the measure of effort. Index series are as described in Figure B2 and Table B4. The geometric mean of each series has been standardised to equal 1.0.

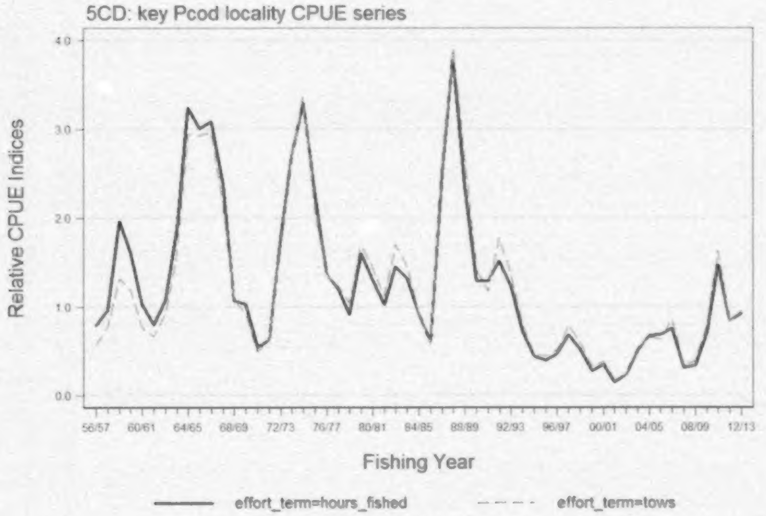


Figure B4. Comparison of two effort measures (hours fished and number tows) for 5CD (Hecate Strait) Pacific Cod arithmetic CPUE (Eq. B1A) from 1956/57 to 2012/13. Plotted index series based on key Pcod localities. The geometric mean of each series has been standardised to equal 1.0.

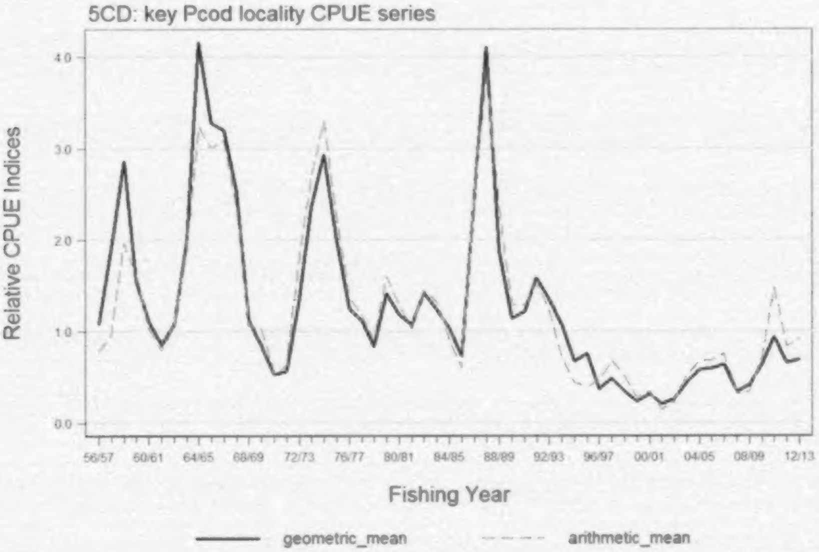
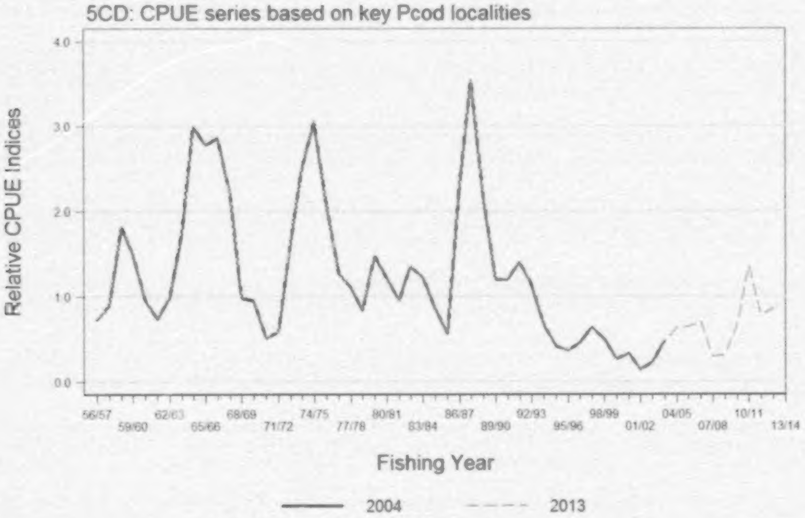


Figure B5. Comparison of arithmetic (Eq. B1) and geometric (Eq. B2) CPUE series calculated for 5CD (Hecate Strait) Pacific Cod from 1956/57 to 2012/13. Both series are based on the same underlying data using key Pcod localities. The geometric mean of each series has been standardised to equal 1.0.



Each relative series scaled so that the geometric mean=1.0 from 56/57 to 03/04

Figure B6. Comparison of arithmetic CPUE (Eq. B1) index series based on Pcod key localities by assessment year for 5CD (Hecate Strait) Pacific Cod from 1956/57 to 2012/13, from Sinclair and Starr (2005) (black line) and the current 5CD assessment (red line).

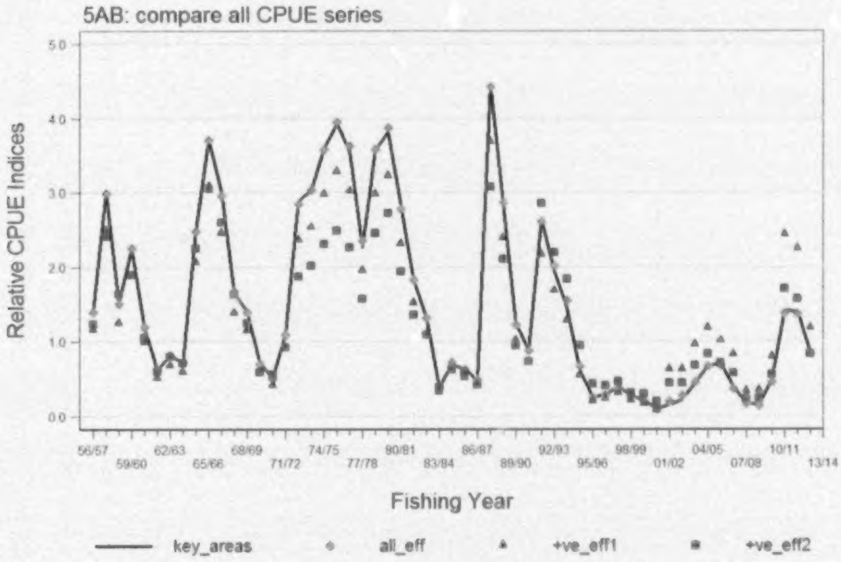


Figure B7. Plot of four arithmetic CPUE (Eq. B1) indices for Queen Charlotte Sound (5AB) Pacific Cod using hours fished as the measure of effort. Index series are described in Figure B2 and Table B4. The geometric mean of each series has been standardised to equal 1.0.

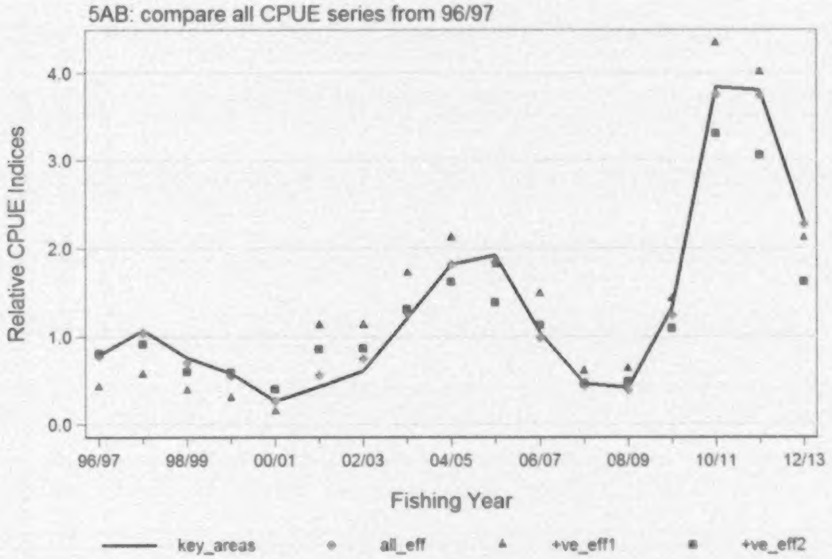


Figure B8. Plot of four arithmetic CPUE (Eq. B1) index series for 5AB (Queen Charlotte Sound) Pacific Cod from 1996/97 to 2012/13 using hours fished as the measure of effort. Index series are described in Figure B2 and Table B4. The geometric mean of each series has been standardised to equal 1.0.

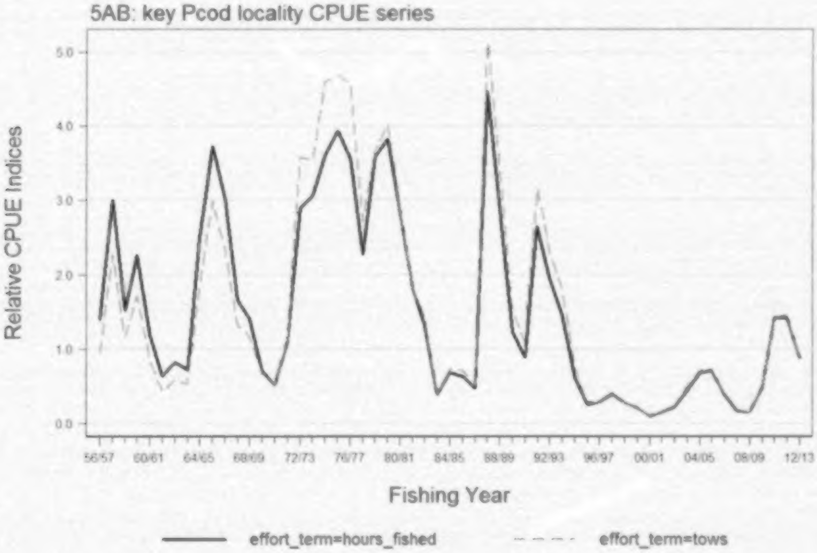


Figure B9. Comparison of two effort measures (hours fished and number tows) for 5AB (Queen Charlotte Sound) Pacific Cod arithmetic CPUE (Eq. B1) from 1956/57 to 2012/13. Plotted index series based on key Pcod localities. The geometric mean of each series has been standardised to equal 1.0.

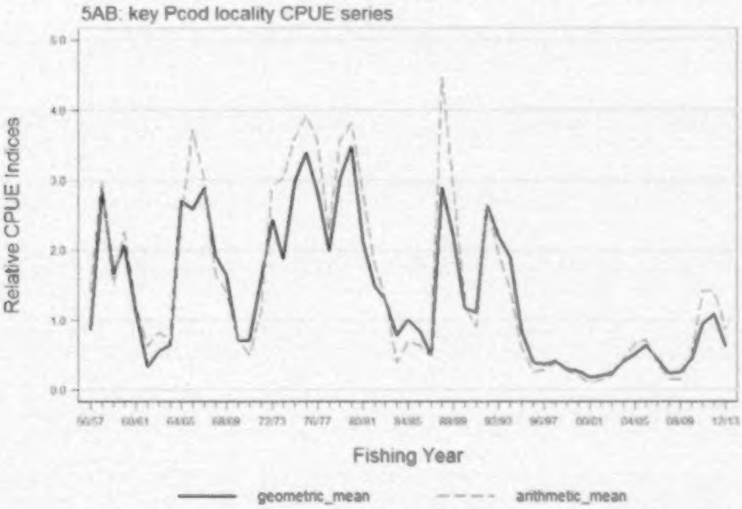


Figure B10. Comparison of arithmetic (Eq. B1) and geometric (Eq. B2) CPUE series calculated for 5AB (Queen Charlotte Sound) Pacific Cod from 1956/57 to 2012/13. Both series are based on the same underlying data using key Pcod localities. The geometric mean of each series has been standardised to equal 1.0.

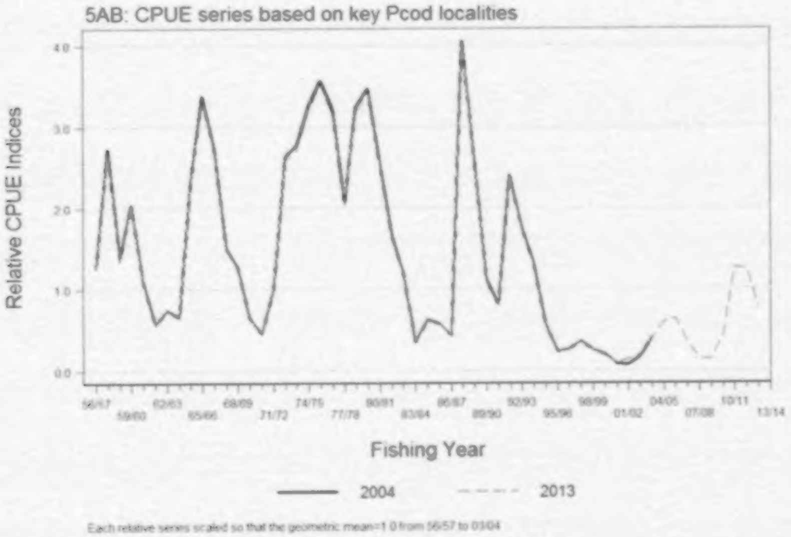


Figure B11. Comparison of arithmetic CPUE (Eq. B1) index series based on Pcod key localities by assessment year for 5AB (Queen Charlotte Sound) Pacific Cod from 1956/57 to 2012/13, from Sinclair and Starr (2005) (black line) and the current 5AB assessment (red line).

Table B1. List of data selection criteria used to filter data for the calculation of Pacific Cod CPUE indices.

GFCatch (1 April 1956–31 December 1995)

1.	"Source"=1 or "Source"=2	keep: 1="Trawl trip report", 2="Trawl sales slip" drop: 3 & 4 (longline), 5 & 6 (trap)
2.	"Gear" <>4 and <> 6 and <> 7	keep: gear= 0–3, 5, 8 & 9 (all trawl codes) drop: gear 4="Shrimp trawl", 6="Gillnet Drum", and 7="Danish seine"
3.	assign utilisation categories 1–3, 5, and 7 to "landed" catch and utilisation categories 4 and 6 to "discard" catch	1&2= "food", 3= "reduction", 4= "dump"; 5= "bait"; 6= "discard", 7= "no sales slip"
4.	use kg=2.2046 lb as conversion factor	GFCatch data reported in pounds

PacHarvTrawl (16 February 1996–31 March 2007) & GFFOS (1 April 2007–31 March 2013)

5.	"Success code"<=1 and "Success_code"<>NULL	keep: 0="Unknown", 1="Fully usable" drop: all success code>1
6.	Drop all data from Hecate St. monitoring survey (2002–2004)	11 trips dropped representing 412 tows
7.	drop tows numbered "999" (PacHarvTrawl) or "0" (GFFOS)	these are dummy tow numbers assigned to species landings which are observed at dockside but missed by the on-board observer

All data sources

8.	Drop all tows or event records with no catch or discard of any species	Includes some tows with "success_code"=0 or "success_code"=1 in PacHarvTrawl
9.	Drop all tows or event records with where depth=NULL or depth=0 or depth>150 m	In GFCatch, all three depth fields (min_depth, avg_depth & max_depth) =0
10.	Drop all tows or event records with where hours_fished=NULL or hours_fished=0	Field names: GFCatch="time" PacHarv="duration" GFFOS="duration"

Table B2. Algorithm used to convert depth information in GFCatch into a single usable field.

$$\text{Depth}=\frac{(\text{min\_depth}+\text{max\_depth})}{2}\ \text{if min\_depth<>0\&min\_depth<>NULL \&max\_depth<>0\&max\_depth<>NULL}$$

Depth=min_depth if max_depth==0||max_depth==NULL

Depth=max_depth if min_depth==0||min_depth==NULL

Depth (m)=Depth(fathoms) * 1.8288

Table B3. Description of four CPUE analyses performed on Pacific Cod catches from Hecate Strait (5CD) and Queen Charlotte Sound (5AB). Analyses A to C were performed on catch and effort data from all of 5AB or 5CD while Analysis D was performed on the areas listed in Table B4.

	Figure code	Description
A.	all_eff	Catch and effort are summed without regard to target species or location of capture. This analysis is a continuation of the CPUE analysis provided for the 2001 Hecate St. assessment.
B.	+ve_eff1	Catch and effort are summed as in Analysis A up to 31 March 2001 (the end of the 2000/01 fishing year). After that date (when the TAC was dropped to 200 t) only tows which captured Pacific Cod are included in the analysis to allow for the fact that fishermen were actively avoiding Pacific Cod after that date.
C.	+ve_eff2	Only catch and effort from tows or events which actually caught Pacific Cod are included in the analysis, regardless of the year of capture.
D.	key_areas	Only catch and effort from key Pacific Cod localities (Table B4, Figure B1) were included in the analysis.

Table B4. DFO localities used to define "key Pacific Cod areas" for Queen Charlotte Sound and Hecate Strait Pacific Cod.

MAJOR_STAT_AREA_CDE	MINOR_STAT_AREA_CDE	LOCALITY_NAME	LOCALITY_CODE
Queen Charlotte Sound (5AB)			
5	11	CAPE SCOTT SPIT	2
5	11	MEXICANA	3
5	11	TOPKNOT	4
6	8	NE GOOSE	1
6	8	SE GOOSE	2
6	8	NW GOOSE	3
6	8	SW GOOSE	4
Hecate Strait (5CD)			
7	2	REEF ISLAND	3
7	2	WEST HORSESHOE	1
7	6	EAST HORSESHOE	10
8	4	TWO PEAKS	2
8	4	BUTTERWORTH	1
8	5	WHITE ROCKS	1
8	5	SHELL GROUND	3

Table B5. Arithmetic (Eq. B1) and geometric (Eq. B2) CPUE indices (kg/h) for Queen Charlotte Sound and Hecate Strait Pacific Cod. The analyses in this table are defined in Table B3.

	Queen Charlotte Sound (5AB)						Hecate Strait (5CD)					
	Arithmetic mean				Geometric mean		Arithmetic mean				Geometric mean	
FYear	A	B	C	D	A	D	A	B	C	D	A	D
56/57	99.3	99.3	151.3	99.3	49.2	49.2	194.9	194.9	368.8	227.8	180.3	174.4
57/58	212.7	212.7	293.8	212.7	161.1	161.1	316.2	316.2	543.0	279.1	385.8	310.0
58/59	107.3	107.3	199.6	107.3	94.5	94.5	464.6	464.6	654.8	568.7	449.1	460.1
59/60	159.9	159.9	230.9	159.9	117.2	117.2	354.4	354.4	396.6	470.0	238.0	250.7
60/61	84.8	84.8	129.4	84.8	63.2	63.2	284.4	284.4	327.9	299.7	170.0	179.1
61/62	44.5	44.5	73.3	44.5	19.2	19.2	210.4	210.4	254.2	230.8	133.3	138.1
62/63	58.0	58.0	97.3	58.0	31.5	31.5	272.9	272.9	313.3	310.9	155.7	172.3
63/64	51.1	51.1	87.0	51.1	37.0	37.0	495.8	495.8	545.4	545.1	283.2	320.5
64/65	176.1	176.1	275.0	176.1	153.3	153.3	874.8	874.8	963.9	939.5	634.2	670.1
65/66	263.4	263.4	371.8	263.4	146.6	146.6	894.0	894.0	924.6	872.5	544.2	526.9
66/67	210.1	210.1	316.2	213.3	161.6	163.5	824.9	824.9	917.2	896.1	488.8	515.9
67/68	118.7	118.7	198.0	116.8	110.2	108.3	650.7	650.7	752.7	690.6	370.5	406.1
68/69	98.7	98.7	152.0	99.9	91.7	93.4	329.8	329.8	382.0	307.8	184.0	181.4
69/70	50.2	50.2	72.0	50.6	39.7	39.7	252.8	252.8	289.8	298.2	124.4	136.8
70/71	35.4	35.4	67.4	35.9	40.3	40.3	121.9	121.9	150.6	157.9	65.1	85.2
71/72	77.5	77.5	112.5	78.5	88.0	89.1	156.9	156.9	193.3	182.1	77.3	91.9
72/73	201.9	201.9	228.3	205.1	135.7	137.7	425.3	425.3	452.6	513.9	174.1	219.2
73/74	216.0	216.0	246.1	215.4	108.9	105.8	649.4	649.4	724.5	781.6	301.6	379.7
74/75	254.6	254.6	280.8	254.6	168.6	168.6	823.2	823.2	860.1	957.9	378.5	473.0
75/76	280.3	280.3	303.0	278.7	199.7	192.5	559.3	559.3	607.0	651.6	260.3	321.9
76/77	257.8	257.8	275.1	251.5	165.5	160.2	347.9	347.9	394.3	397.3	176.2	201.6

	Queen Charlotte Sound (5AB)						Hecate Strait (5CD)					
	Arithmetic mean				Geometric mean		Arithmetic mean				Geometric mean	
FYear	A	B	C	D	A	D	A	B	C	D	A	D
77/78	166.9	166.9	191.5	160.6	118.2	112.9	313.2	313.2	355.4	345.2	157.4	180.2
78/79	254.4	254.4	298.2	253.2	172.0	171.0	243.8	243.8	307.6	262.8	119.9	134.3
79/80	275.2	275.2	332.1	270.7	199.2	197.4	404.7	404.7	464.3	463.7	196.7	227.4
80/81	197.5	197.5	236.8	200.0	118.1	120.5	330.6	330.6	387.8	376.6	163.3	190.2
81/82	129.6	129.6	165.4	128.9	87.1	84.6	266.4	266.4	317.7	296.7	149.5	172.7
82/83	93.8	93.8	133.0	93.8	75.0	73.4	365.2	365.2	420.3	421.5	192.4	228.7
83/84	27.6	27.6	48.0	27.4	46.8	44.0	341.6	341.6	408.2	384.3	173.8	200.7
84/85	51.8	51.8	77.9	49.1	58.9	56.9	238.4	238.4	286.6	267.2	141.7	167.5
85/86	44.2	44.2	70.0	45.0	47.7	47.7	203.1	203.1	246.1	175.4	117.1	117.5
86/87	34.8	34.8	51.8	34.2	29.7	28.5	644.1	644.1	742.6	724.1	337.1	402.9
87/88	314.3	314.3	374.4	316.2	162.6	164.1	1034.	1034.	1156.	1110.	590.8	662.1
88/89	203.8	203.8	256.8	203.3	123.6	124.6	613.0	613.0	721.2	681.2	259.3	302.4
89/90	86.8	86.8	114.8	87.5	64.2	66.0	306.8	306.8	376.9	374.5	149.4	184.6
90/91	62.9	62.9	90.1	63.3	61.9	63.1	317.1	317.1	409.3	374.1	206.5	196.1
91/92	185.1	185.1	348.3	187.3	147.3	149.3	438.1	438.1	643.1	440.2	259.4	255.5
92/93	143.8	143.8	267.8	137.4	124.2	124.3	292.3	292.3	457.5	357.7	177.5	217.5
93/94	109.8	109.8	223.8	102.7	109.8	107.9	171.7	171.7	308.9	209.2	144.1	173.1
94/95	47.4	47.4	115.7	43.4	49.7	47.4	97.1	97.1	192.5	129.0	85.9	108.7
95/96	17.9	17.9	52.8	18.1	23.1	23.1	99.7	99.7	205.2	115.1	104.8	122.6
96/97	20.2	20.2	50.4	20.5	21.5	21.0	110.5	110.5	147.8	136.3	44.7	59.8
97/98	27.3	27.3	56.8	28.2	23.4	23.7	166.3	166.3	205.9	197.6	65.8	79.3
98/99	18.3	18.3	37.7	19.9	16.9	17.5	114.3	114.3	153.9	149.6	42.4	54.7
99/00	14.4	14.4	36.7	15.2	15.9	15.7	74.6	74.6	104.7	81.5	29.7	37.8
00/01	7.0	7.0	24.9	7.0	10.7	10.7	74.6	74.6	110.4	100.5	37.2	51.6

FYear	Queen Charlotte Sound (5AB)						Hecate Strait (5CD)					
	Arithmetic mean				Geometric mean		Arithmetic mean				Geometric mean	
	A	B	C	D	A	D	A	B	C	D	A	D
01/02	14.5	53.8	53.8	11.1	13.0	11.7	32.3	57.8	57.8	42.3	27.8	34.3
02/03	19.5	54.0	54.0	15.8	15.5	14.3	49.1	71.4	71.4	67.7	31.1	41.8
03/04	32.8	82.3	82.3	31.6	23.7	23.6	92.8	131.3	131.3	149.0	40.7	70.7
04/05	47.6	101.5	101.5	47.7	29.7	29.7	127.7	182.0	182.0	195.9	58.9	94.4
05/06	48.2	86.8	86.8	50.5	34.7	36.0	155.7	194.2	194.2	199.3	79.1	95.7
06/07	25.8	71.1	71.1	27.5	25.6	25.5	162.4	232.5	232.5	218.9	77.0	103.0
07/08	11.2	28.1	28.1	11.9	12.9	13.4	84.3	130.1	130.1	91.5	46.8	54.7
08/09	10.2	30.4	30.4	11.1	15.1	15.1	79.3	125.3	125.3	99.0	49.7	66.4
09/10	32.4	68.3	68.3	34.7	25.0	26.2	148.3	195.9	195.9	205.7	66.2	104.8
10/11	97.9	208.4	208.4	100.5	52.0	53.3	319.9	400.6	400.6	427.4	104.0	150.7
11/12	98.4	192.9	192.9	100.3	57.4	61.2	227.3	274.2	274.2	243.9	93.6	106.1
12/13	60.1	102.4	102.4	61.7	32.9	35.7	174.9	210.7	210.7	266.7	68.6	111.8

APPENDIX C: MEAN WEIGHT DATA

INTRODUCTION

The methods used to calculate annual mean weights in the commercial catch are described in this Appendix. The methods differ for Area 5CD and Area 5AB, following the recommendations of the review committee at the January 2014 Centre for Science Advice Pacific Region (CSAP) review meeting, where the first draft of this working paper was reviewed.

Just before the January 2014 CSAP meeting, it was discovered that the query for the extraction of the commercial length samples from the biological database (GFBio) was flawed (details are provided below). It was also discovered that inadequate sample sizes had been used in the calculation of annual mean weights in Area 5AB for recent years. One reviewer also noted that individual fish lengths should have been converted to weights using the length-weight parameters, rather than converting the mean length of samples to mean weights.

Taking results of sensitivity analyses into consideration, the CSAP review committee recommended proceeding with the Area 5CD assessment model for generating catch advice using the flawed query and the conversion of length to weight as was originally presented.

For Area 5AB, however, the committee recommended re-running the model with annual mean weights using all available length samples, based on the corrected (updated) length query, and converting individual lengths to weights. This was mainly to address the problem of inadequate sample sizes of length data. However, it was recognized that if the models were to be re-run with new annual mean weights, these data should reflect the most up-to-date analysis.

Therefore, the analysis for Area 5CD, which was accepted by the review committee, is based on the original 2013 query and analysis, while the analysis for Area 5AB is based on an updated 2014 query and analysis. The impact of using the original query on estimates of biomass and recruitment in Area 5CD was relatively minor (see note at the end of this Appendix).

Further exploration on the extraction and application of these data has been highlighted as a priority research recommendation.

Throughout this Appendix, we refer to the original, flawed 2013 query as the "Original" query and the corrected 2014 query as the "Updated" query.

METHODS

Length data

Area 5CD

The January 2014 CSAP review committee recommended no changes to the Area 5CD assessment following the review meeting, so the original analysis is presented in this Appendix and was used in the stock assessment model.

Length data from the commercial trawl fishery were selected from the GFBio database using the criteria shown in Table C1, i.e., the "Original" query. The number of resulting samples in each category is shown in Table C2.

The flaw with the Original query concerned extraction of length samples under the category "Unsorted". Prior to 1996, the majority of fish measured in commercial samples were measured at port, and were categorized as "Keepers" (i.e., fish that had not been released at sea). After 1996, most samples were measured at sea by onboard observers and were therefore reported in either a general "Unsorted" category or as "Keepers" or "Discards".

In the Original query, many samples categorized as "Unsorted" may actually have been solely comprised of larger fish ("Keepers") or released fish ("Discards"). Within the GFBio database there are two fields that must be used in combination to determine the source of a sample: species_category_code from the Catch table and sample_source_code in the Sample table. Failure to include both fields can, and did, result in incorrect categorization of fish, with too many fish assigned to the "Unsorted" category and some fish being double-counted.

The introduction of onboard observers in 1996 resulted in a shift from the majority of fish being reported in the "Keepers" category prior to 1996, to the "Unsorted" category from 1996 onwards. For calculation of annual mean weights, a decision was made for Area 5CD to use "Keepers" samples prior to 1996 and "Unsorted" samples after this. This decision was made to maintain consistency with the approach used in the previous assessment of Pacific Cod (Sinclair and Starr 2005).

Table C1. Criteria used to select samples from the GFBio database used for calculating mean weights for Area 5CD

1.	Select TRIP_SUB_TYPE = 1 or 4	1=Non-observed domestic 4=observed domestic
2.	Select major PMFC areas =5CD or 5AB	As required for the analysis
3.	Select GEAR_CODE = 1	Bottom trawl only
4.	Select SPECIES_CATEGORY_CODE = 1 or 3	1=Unsorted; 3=Keepers (as required for the analysis)
5.	Select SAMPLE_TYPE_CODE = 1 or 2 or 6 or 7	1=total catch 2=random 6=random from randomly assigned set 7=random from set after randomly assigned set
6.	Drop: SAMPLE_ID: 173726, 173740, 191471, 184243, 184159, 215903, 223726	These samples were coded as being from Pacific Cod but have a size composition inconsistent with the species. These samples were therefore excluded from further analysis.
7.	Fishing years from 1 April 1956 to 31 March 2013, separated into three-month quarters: 1=Apr-Jun; 2=Jul-Sep; 3=Oct-Dec; 4=Jan-Mar.	Quarters coded sequentially for the analysis

Table C2. Number of samples by year in Area 5CD in the three categories described in Table C3 for combined non-observed domestic and observed domestic trips from 1956 to 2012. '–': no data.

Fishing	5CD				
Year	Unknown	Unsorted	Keepers	Discarded	Total
1956	1	–	8	–	9
1957	–	–	*16*	–	*16*
1958	–	–	42	–	42
1959	–	–	37	–	37
1960	–	–	47	–	47
1961	–	–	53	–	53
1962	–	2	32	–	34
1963	–	–	46	–	46
1964	–	–	70	–	70
1965	–	10	62	–	72
1966	–	–	72	–	72
1967	–	43	52	–	95
1968	–	–	45	–	45
1969	–	–	28	–	28
1970	–	–	18	–	18
1971	–	–	14	–	14
1972	–	11	14	–	25
1973	–	15	34	3	52
1974	–	12	43	–	55
1975	–	56	34	–	90
1976	–	4	33	–	37
1977	–	–	48	–	48
1978	–	21	55	2	78
1979	–	65	70	–	135
1980	–	21	21	–	42
1981	–	38	21	5	64
1982	–	54	42	4	100
1983	–	74	33	–	107
1984	–	105	29	–	134
1985	–	109	17	–	126
1986	–	5	35	–	40
1987	–	64	17	–	81
1988	–	–	17	–	17
1989	–	59	13	–	72
1990	–	11	16	–	27

Fishing	5CD				
Year	Unknown	Unsorted	Keepers	Discarded	Total
1991	–	44	31	–	75
1992	–	–	22	–	22
1993	7	45	34	–	86
1994	–	–	19	–	19
1995	–	14	12	–	26
1996	–	340	17	–	357
1997	–	3	15	–	18
1998	–	65	50	–	115
1999	–	9	22	6	37
2000	–	61	9	–	70
2001	–	82	4	–	86
2002	–	279	–	–	279
2003	–	351	3	–	354
2004	–	214	20	13	247
2005	–	294	6	–	300
2006	–	52	3	–	55
2007	–	148	4	–	152
2008	–	18	2	–	20
2009	–	157	–	–	157
2010	–	43	–	–	43
2011	–	228	–	–	228
2012	–	37	–	–	37
Total	47	3,263	1,516	35	4,861

Area 5AB

The 2014 CSAP Review Committee recommended re-running the Area 5AB stock assessment model with updated annual mean weight data. This was because, inadvertently, only “Keepers” samples had been used to calculate annual mean weights in the original analysis, resulting in very small sample sizes after 1996, and several years with no samples at all. Commercial annual mean weights for Area 5AB are therefore calculated here using length data from all categories for all years, extracted using the Updated query. The criteria for the query are shown in Table C3. The numbers of resulting samples in each category are shown in Table C4.

The analysis for Area 5AB is presented with the caveat that there are large discrepancies between the sampled lengths in the early part of the time series (pre-1996) and the latter part of the time series, and there are several years with very small sample sizes or no data at all (Figure C1 and Table C4). Discrepancies between the early and recent parts of the time series are a result of the introduction of onboard observers in 1996. Prior to this, samples were measured in port and did not include fish released at sea. Length samples in the early part of the time series are therefore biased.

Table C3. Criteria used to select samples from the GFBio database (only used for 5AB analysis).

1. TRIP_SUB_TYPE = 1 or 4	1=Non-observed domestic 4=Observed domestic
2. SPECIES_CODE = 222	Pacific Cod
3. ACTIVITY_CODE is null	To avoid samples taken during the Hecate Strait Pacific cod monitoring survey
4. GEAR_CODE = 1	Bottom trawl
5. To assign the samples to unsorted, keeper or discard categories must consider both fields	Species_category_code 1 = unsorted, 3 = keepers, 4 = discards Sample_source_code 0 = unknown, 1 = unsorted, 2 = keepers, 3 = discards
SPECIES_CATEGORY_CODE = 1 and SAMPLE_SOURCE_CODE = 1 or Null	Sample source = unsorted
SPECIES_CATEGORY_CODE = 1 and SAMPLE_SOURCE_CODE = 2 OR SPECIES_CATEGORY_CODE = 3 and SAMPLE_SOURCE_CODE = 2 or Null	Sample source = keepers
SPECIES_CATEGORY_CODE = 1 and SAMPLE_SOURCE_CODE = 3 OR SPECIES_CATEGORY_CODE = 4 and SAMPLE_SOURCE_CODE = 3 or Null	Sample source = discards
6. SAMPLE_TYPE_CODE = 1 or 2 or 6 or 7	1=total catch 2=random 6=random from randomly assigned set 7=random from set after randomly assigned set
7. SAMPLE_ID <> 173726, 173740, 191471, 184243, 184159, 215903, 223726	These samples were coded as being from Pacific cod but have a size composition inconsistent with the species. These samples were therefore excluded from further analysis.
8. FISHING YEAR	April 1 – March 31. Based on end of fishing event (fe_begin_retrieval_time)
9. QUARTER	Based on end of fishing event (fe_begin_retrieval_time)

Table C4. Number of samples by year in Area 5AB in the three categories described in Table C3 for combined non-observed domestic and observed domestic trips from 1956 to 2012. '–': no data.

Fishing	5AB			
Year	Unsorted	Keepers	Discarded	Total
1956	–	7	–	7
1957	–	24	–	24
1958	–	20	–	20
1959	–	16	–	16
1960	–	22	–	22
1961	–	18	–	18
1962	–	15	–	15
1963	–	12	–	12
1964	–	24	–	24
1965	–	17	–	17
1966	–	27	–	27
1967	–	27	–	27
1968	–	21	–	21
1969	–	14	–	14
1970	–	4	–	4
1971	–	7	–	7
1972	8	5	3	16
1973	–	3	2	5
1974	–	4	–	4
1975	–	5	–	5
1976	–	14	–	14
1977	–	20	–	20
1978	4	21	–	25
1979	1	8	–	9
1980	2	8	–	10
1981	18	3	9	30
1982	11	11	1	23
1983	1	2	–	3
1984	–	–	–	–
1985	–	3	–	3
1986	–	2	–	2
1987	–	5	–	5
1988	–	–	–	–
1989	–	1	–	1

Fishing	5AB			
Year	Unsorted	Keepers	Discarded	Total
1990	–	3	–	3
1991	–	5	–	5
1992	–	–	–	–
1993	–	1	–	1
1994	–	6	–	6
1995	–	–	–	–
1996	2	–	–	2
1997	1	1	–	2
1998	6	9	4	19
1999	2	8	–	10
2000	–	2	1	3
2001	2	–	–	2
2002	8	2	1	11
2003	25	4	1	30
2004	63	3	5	71
2005	37	5	–	42
2006	22	1	–	23
2007	3	1	–	4
2008	3	–	–	3
2009	9	2	–	11
2010	33	4	–	37
2011	17	5	–	22
2012	12	2	–	14
Total	290	462	27	779

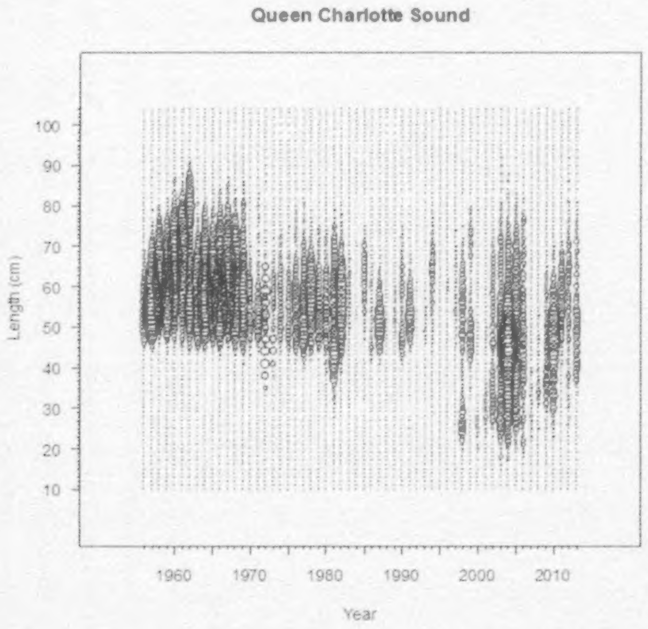


Figure C1. Raw length frequency data from the Updated query for Area 5AB showing all length samples. Blue dots indicate zeros.

Calculation of Annual Mean Weight

The calculation of annual mean weight was done in the following steps. Note the reversal of Steps 1 and 2 for Area 5CD and 5AB, reflecting the updated analysis used for Area 5AB.

Two different approaches were taken to define the values to use for the a^q and b^q constant parameters. "Approach 1" followed the approach of Westrheim (1996), who used a different length-weight relationship for the January-March quarter than for the other quarters, as shown for "Approach 1" (Table C5). "Approach 2" used the same length-weight relationship in all quarters (Table C5).

Area 5CD

Step 1. From the selected data set, calculate the mean length (L_j) for each Sample ID (j):

$$L_j = \sum_{i=1}^{N_j} l_{ij} \Big/ N_j \qquad \text{Eq. C1a}$$

where N_j is the number of length measurements l_{ij} in Sample ID (j)

Step 2. Convert the mean length (L_j) for each Sample ID (j) to mean weight (W_j):

$$W_j = a^q L_j^{b^q} \qquad \text{Eq. C2a}$$

where a^q and b^q are constant length-weight parameters specific to the quarter when the SampleID (j) was taken (Table C5).

Table C5. Quarterly length-weight parameters for Approach 1 and Approach 2. Source: Westrheim 1996

	Approach 1		**Approach 2**	
Quarter	a^q	b^q	a^q	b^q
1	7.377E-06	3.0963	7.377E-06	3.0963
2	7.377E-06	3.0963	7.377E-06	3.0963
3	7.377E-06	3.0963	7.377E-06	3.0963
4	4.988E-06	3.2117	7.377E-06	3.0963

Area 5AB

Step 1. Convert individual length (l_i) in each Sample ID (j) to weight (w_i):

$$w_i = a^q l_i^{b^q} \qquad \text{Eq. C1b}$$

where a^q and b^q are constant length-weight parameters specific to the quarter when the SampleID (j) was taken (Table C5).

Step 2. From the selected data set, calculate the mean weight (Wj) for each Sample ID (j):

$$W_j = \sum_{i=1}^{N_j} w_{ij} \Big/ N_j \qquad \text{Eq. C2b}$$

where N_j is the number of weights w_{ij} in Sample ID (j)

Both Areas

Step 3. The mean weight (W_s) for each sequential quarter was then calculated, weighted by the sample weight of Pacific Cod (S_j) in each SampleID (j)

$$W_s = \sum_{j=1}^{K_s} W_{js} S_{js} \Big/ \sum_{j=1}^{K_s} S_{js} \qquad \text{Eq. C3}$$

where K_j is the number of SampleIDs (j) in sequential quarter (s), where sequential quarter is a unique identifier for each quarter in the time series.

Step 4. The mean weight (W_f) for a fishing year was calculated in one of two ways: A) by averaging the quarterly mean weight weighted by the commercial catch of Pacific Cod (C_s) during sequential quarter (s); or B) taking the average of the sample quarterly mean weight:

$$W_f^A = \sum_{s=1}^{4} W_s C_s \Big/ \sum_{s=1}^{4} C_s \qquad \text{Eq. C4A}$$

$$W_f^B = \sum_{s=1}^{4} W_s \Big/ 4 \qquad \text{Eq. C4B}$$

RESULTS

Area 5CD

Annual mean weights resulting from the four alternative approaches are presented in Figure C2 and Table C6. The effect of using different length-weight parameters (Table C5) in Approaches 1 and 2 was almost negligible, with the main differences arising from the choice of whether or not to weight the annual mean weights by the catch data.

As noted above, length samples coded as “Keepers” were excluded after 1995 in the Area 5CD analysis. Length frequency distributions and cumulative length-frequency distributions in the “Keepers” and “Unsorted” categories from the original length query are shown in Figures D3 and D4. See also note at the end of this Appendix.

For consistency with the previous assessment (Sinclair and Starr 2004) annual mean weights resulting from “Approach 2A” were used in the stock assessment (indicated with an asterisk in Table C6).

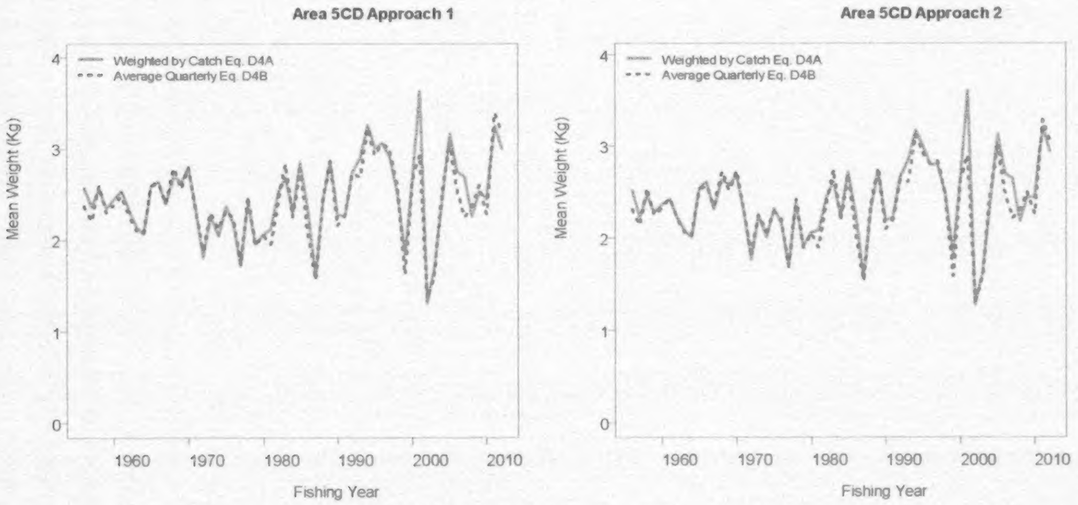


Figure C2. Annual mean weight estimates for Area 5CD, based on "Keepers" samples prior to 1996 and "Unsorted" length samples from 1996 to 2012. Approach 1 (left) and Approach 2 (right) represent alternative treatments of the length-weight relationship (Table C5).

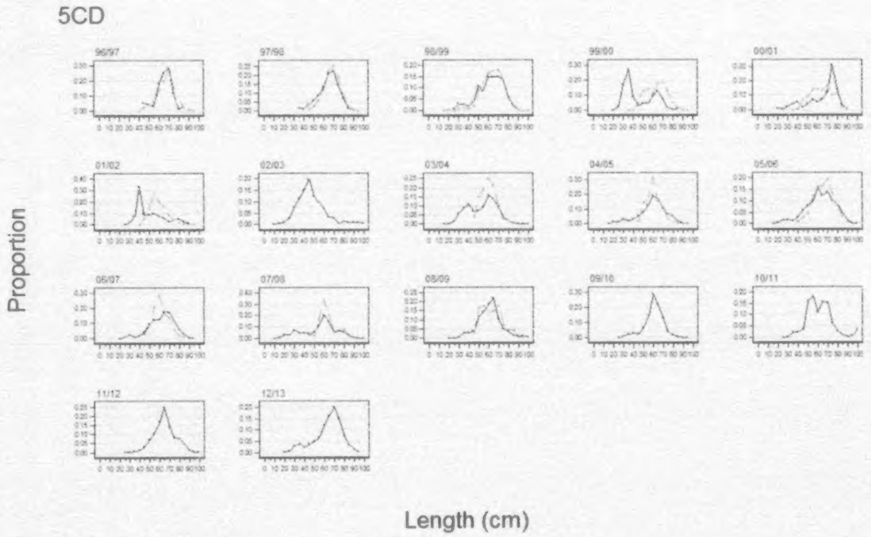


Figure C3. Comparison of "Keepers" (red) and "Unsorted" (black) annual length frequency distributions for Pacific Cod in Area 5CD, from the original length query. Length frequency distributions have been combined across samples based on sampled catch weight only.

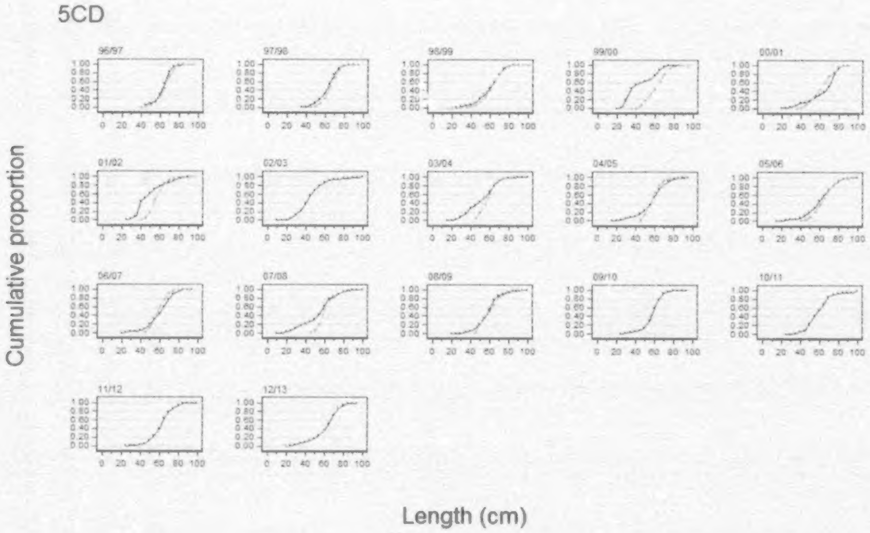


Figure C4. Comparison of "Keepers" (red) and "Unsorted" (black) cumulative annual length frequency distributions for Pacific Cod in 5CD, from the original length query. Length frequency distributions have been combined across samples based on sampled catch weight only.

Table C6. Annual mean weight estimates by fishing year for ***Area 5CD****, based on "Keepers" length samples prior to 1996 and "Unsorted" length samples 1996-2012. The data stream used in the stock assessment is indicated with an asterisk.*

	Approach 1		**Approach 2**	
	Commercial weights Eq D4a	**No commercial weights Eq D4b**	***Commercial weights Eq D4a**	**No commercial weights Eq D4b**
1956	2.573	2.374	2.517	2.313
1957	2.362	2.207	2.229	2.142
1958	2.550	2.597	2.469	2.543
1959	2.344	2.299	2.276	2.255
1960	2.437	2.381	2.361	2.332
1961	2.536	2.481	2.424	2.430
1962	2.327	2.265	2.224	2.217
1963	2.146	2.099	2.091	2.058
1964	2.065	2.081	2.013	2.038
1965	2.600	2.592	2.548	2.528
1966	2.643	2.629	2.610	2.575
1967	2.394	2.394	2.316	2.346
1968	2.703	2.790	2.637	2.730
1969	2.628	2.566	2.582	2.519
1970	2.787	2.795	2.687	2.737
1971	2.329	2.319	2.294	2.276
1972	1.806	1.886	1.773	1.842
1973	2.257	2.298	2.241	2.256
1974	2.038	2.119	2.008	2.074
1975	2.369	2.331	2.324	2.283
1976	2.178	2.242	2.163	2.205
1977	1.718	1.725	1.703	1.691
1978	2.433	2.473	2.389	2.428
1979	1.956	1.937	1.918	1.899
1980	2.059	2.050	2.059	2.050
1981	2.116	1.942	2.085	1.902
1982	2.517	2.420	2.430	2.362
1983	2.688	2.828	2.625	2.741
1984	2.305	2.246	2.240	2.191
1985	2.853	2.782	2.719	2.694
1986	2.300	2.053	2.222	2.018
1987	1.594	1.565	1.556	1.532

	Approach 1		Approach 2	
	Commercial weights Eq D4a	No commercial weights Eq D4b	*Commercial weights Eq D4a	No commercial weights Eq D4b
1988	2.431	2.452	2.329	2.394
1989	2.863	2.859	2.732	2.757
1990	2.274	2.158	2.191	2.096
1991	2.261	2.257	2.228	2.203
1992	2.740	2.729	2.667	2.634
1993	2.900	2.680	2.844	2.612
1994	3.260	3.225	3.172	3.124
1995	3.004	2.928	3.004	2.928
1996	3.060	3.060	2.803	2.803
1997	2.916	2.996	2.802	2.850
1998	2.540	2.615	2.498	2.505
1999	1.838	1.625	1.826	1.592
2000	2.661	2.663	2.645	2.635
2001	3.627	2.929	3.602	2.900
2002	1.302	1.354	1.278	1.322
2003	1.693	1.614	1.618	1.574
2004	2.409	2.496	2.343	2.451
2005	3.165	3.069	3.129	3.005
2006	2.749	2.527	2.703	2.479
2007	2.693	2.254	2.649	2.215
2008	2.262	2.351	2.181	2.307
2009	2.524	2.593	2.448	2.502
2010	2.450	2.286	2.440	2.261
2011	3.250	3.384	3.208	3.284
2012	2.994	3.167	2.945	3.052

Area 5AB

Annual mean weights resulting from the four alternative approaches are presented in Figure C5 and Table C7. As for Area 5CD, the effect of using different length-weight parameters (Table C5) in Approaches 1 and 2 was very minor, with more differences arising from the choice of whether or not to weight the annual mean weights by the catch data.

Annual mean weights resulting from "Approach 2A" were used in the stock assessment (indicated with an asterisk in Table C7). There were several years with missing length data (Figure C5, blank years in Table C7). Annual mean weights for these years were interpolated from the average of the mean weights in the previous and following year.

We advise interpreting these annual mean weight data with extreme caution. The time series prior to 1996 can be considered biased due to the absence of lengths from discarded fish (Figure C1). Also, there were very few available samples in many years, especially between 1980 and 2000 (Figure C1, Table C4).

We strongly recommend future research into combining data from Queen Charlotte Sound and Hecate Strait and assessing the two areas as a single stock (see Research Recommendations in the main document).

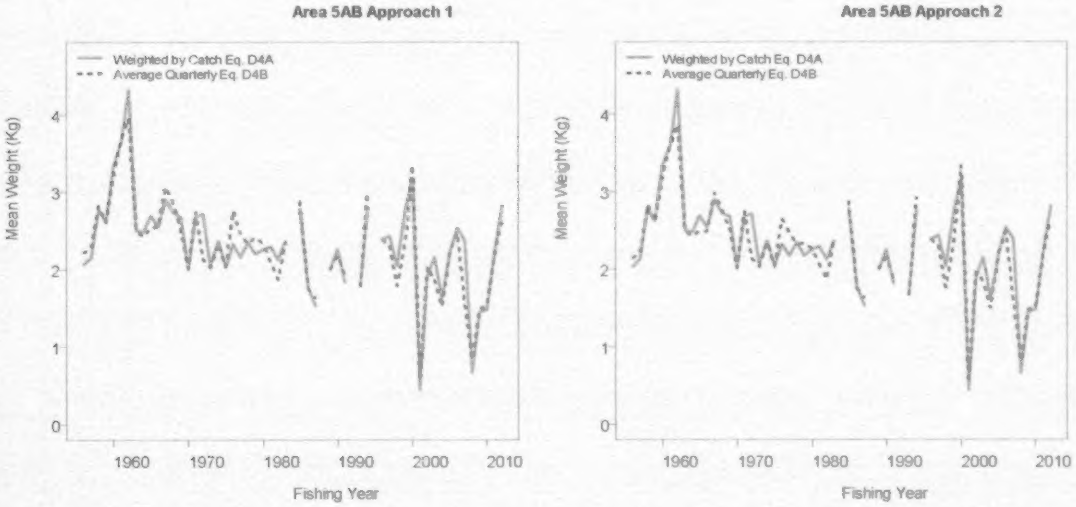


Figure C5. Annual mean weight estimates for Area 5AB, based on all samples. Approach 1 (left) and Approach 2 (right) represent alternative treatments of the length-weight relationship (Table C5). Missing mean weights were interpolated in the assessment.

Table C7. Annual mean weight estimates by fishing year for ***Area 5AB****, using all length samples. '–': no data. The data stream used in the stock assessment is indicated with an asterisk.*

	Approach 1		Approach 2	
	Commercial weights Eq D4a	**No commercial weights Eq D4b**	***Commercial weights Eq D4a**	**No commercial weights Eq D4b**
1956	2.070	2.223	2.028	2.143
1957	2.148	2.268	2.136	2.200
1958	2.780	2.824	2.780	2.824
1959	2.620	2.607	2.620	2.607
1960	3.316	3.190	3.316	3.190
1961	3.648	3.697	3.591	3.594
1962	4.317	3.949	4.306	3.861
1963	2.500	2.492	2.500	2.492
1964	2.478	2.416	2.478	2.416
1965	2.698	2.545	2.692	2.497
1966	2.542	2.550	2.534	2.490
1967	2.909	3.070	2.898	2.983
1968	2.734	2.841	2.712	2.743
1969	2.680	2.516	2.680	2.516
1970	2.008	2.009	2.008	2.009
1971	2.683	2.743	2.683	2.743
1972	2.718	2.141	2.716	2.132
1973	2.063	2.030	2.063	2.030
1974	2.367	2.337	2.367	2.337
1975	2.038	2.037	2.038	2.037
1976	2.330	2.765	2.326	2.645
1977	2.164	2.474	2.164	2.474
1978	2.345	2.326	2.345	2.326
1979	2.206	2.417	2.181	2.332
1980	2.259	2.331	2.249	2.262
1981	2.298	2.090	2.295	2.060
1982	2.128	1.870	2.128	1.870
1983	2.359	2.359	2.359	2.359
1984	–	–	–	–
1985	2.784	2.872	2.784	2.872
1986	1.773	1.753	1.773	1.753
1987	1.531	1.634	1.531	1.634

	Approach 1		Approach 2	
	Commercial weights Eq D4a	No commercial weights Eq D4b	*Commercial weights Eq D4a	No commercial weights Eq D4b
1988	–	–	–	–
1989	2.006	2.006	2.006	2.006
1990	2.269	2.180	2.247	2.150
1991	1.841	1.922	1.812	1.870
1992	–	–	–	–
1993	1.792	1.792	1.669	1.669
1994	2.803	3.018	2.754	2.923
1995	–	–	–	–
1996	2.385	2.385	2.385	2.385
1997	2.432	2.292	2.432	2.292
1998	2.051	1.792	2.043	1.769
1999	2.757	2.351	2.757	2.351
2000	3.174	3.336	3.174	3.336
2001	0.448	0.593	0.448	0.593
2002	1.917	2.032	1.885	1.963
2003	2.158	1.866	2.155	1.851
2004	1.624	1.520	1.620	1.500
2005	2.223	2.248	2.212	2.209
2006	2.537	2.472	2.537	2.472
2007	2.382	1.566	2.382	1.566
2008	0.670	0.842	0.659	0.820
2009	1.454	1.489	1.442	1.475
2010	1.476	1.530	1.472	1.497
2011	2.245	2.233	2.245	2.233
2012	2.820	2.643	2.820	2.643

A note on Area 5CD Annual Mean Weight analysis

The CSAP review committee recommended no changes to the 5CD assessment following the review meeting. The original analysis for Area 5CD has been presented in this Appendix and was used for generating catch advice. To illustrate the impact of this decision, however, the Base Case model for Area 5CD is re-run here, with updated mean weights, using length samples in all categories for all years from the updated length query (Figure C6).

The updated annual mean weight data had very little impact on estimates of biomass and recruitment (Figure C7).

Figure C8 shows that, as for Area 5AB (Figure C1), raw commercial length data for Area 5CD are truncated prior to 1996, reflecting little to no sampling of fish that were released at sea prior to the introduction of onboard observers. This implies that annual mean weights prior to 1996 are biased high, although it is not possible to estimate the magnitude of the bias without knowledge of selectivity in this period. This represents a significant problem with the annual mean weight data in this assessment that is irresolvable with current information.

Comparison of Figure C8a (only "Keepers" prior to 1996, and only "Unsorted" from 1996 onwards) with Figure C8b (all available data) suggests that this bias could be slightly reduced by including all of the available length data in future assessments. In future assessments of the Area 5CD stock, the authors recommend using all available samples from the updated query, as presented above for Area 5AB.

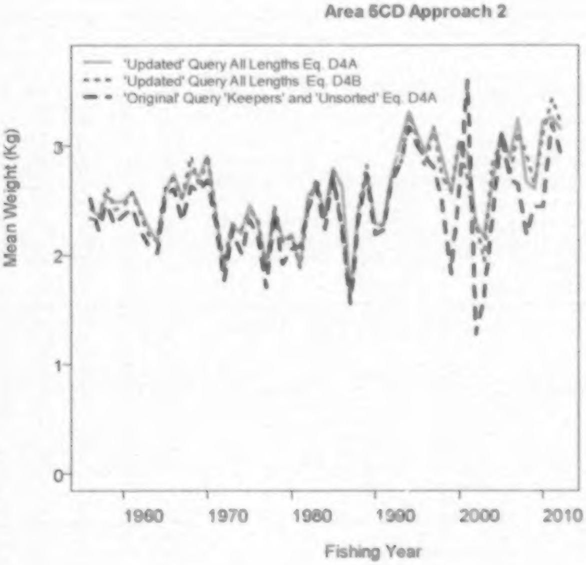


Figure C6. Area 5CD annual mean weights for Area 5CD calculated using the Updated query with all length samples using Eq D.4A (red) and Eq D.4B (blue) for comparison with those calculated from the Original query (black), used in this assessment.

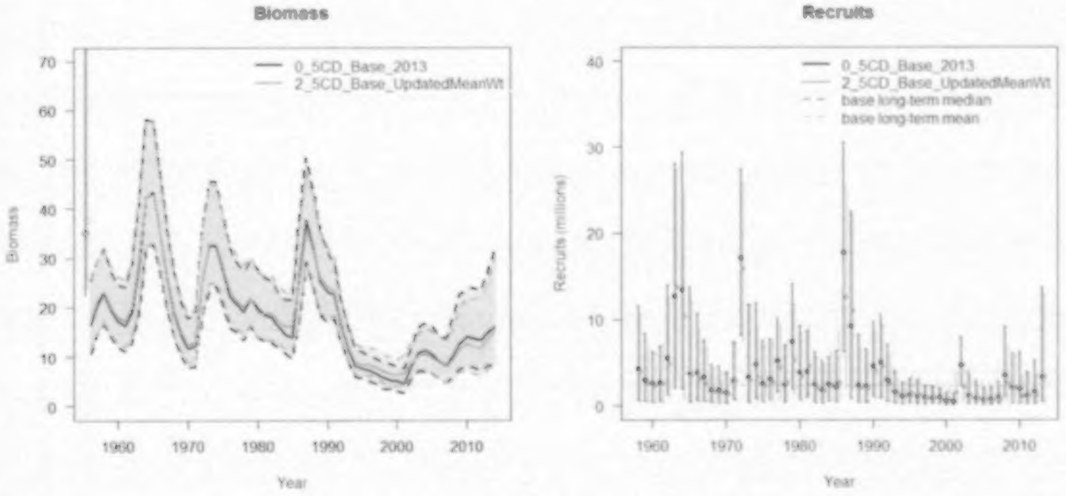


Figure C7. Comparison of posterior estimates of Biomass and Recruits from the current assessment, using annual commercial mean weights calculated from the Original query (black), used in this assessment, compared with estimates obtained using annual commercial mean weights from the Updated query (red).

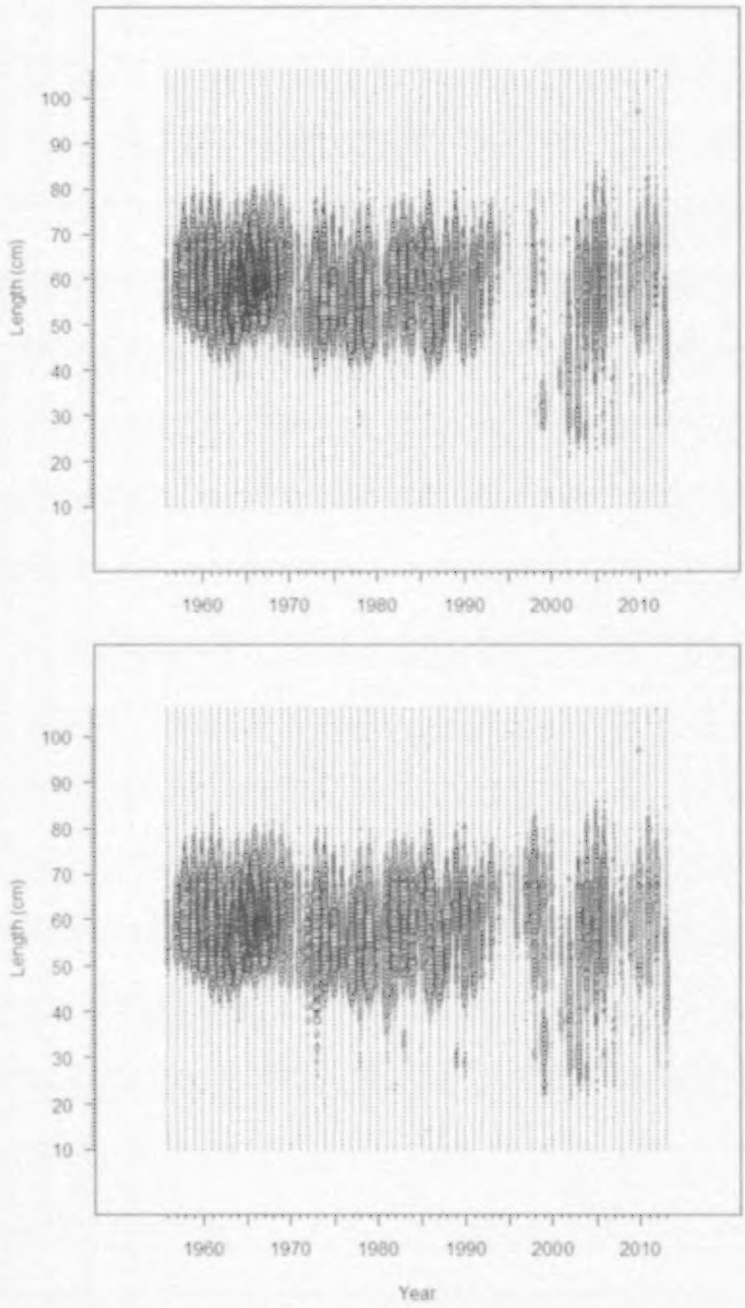


Figure C8a (Top) Raw length frequency data from the Updated query for Hecate Strait with "Keepers" only samples prior to 1996 and "Unsorted" only samples from 1996 onwards; and D8b (Bottom) Raw length frequency data from the Updated query for Hecate Strait showing all length samples. Blue dots indicate zeros.

APPENDIX D: LENGTH-FREQUENCY DATA FOR HECATE STRAIT AND QUEEN CHARLOTTE SOUND

DATA EXTRACTION

Length data from research surveys were extracted from the GFBio database. All specimens were obtained from unsorted catches, i.e., there was no selection based on size. For Area 5CD, individual lengths were extracted from the Hecate Strait Multispecies Assemblage survey (1984-2003) and the Hecate Strait Synoptic survey (2005-2013) (Figure D1). For Area 5AB, individual lengths were extracted from the Queen Charlotte Synoptic survey (2003-2013) (Figure D3).

Commercial length data were extracted from the GFBio database based on the criteria in Table 7. Individual lengths by fishing year and quarter are presented for Area 5CD (Figure D2) and Area 5AB (Figure D4).

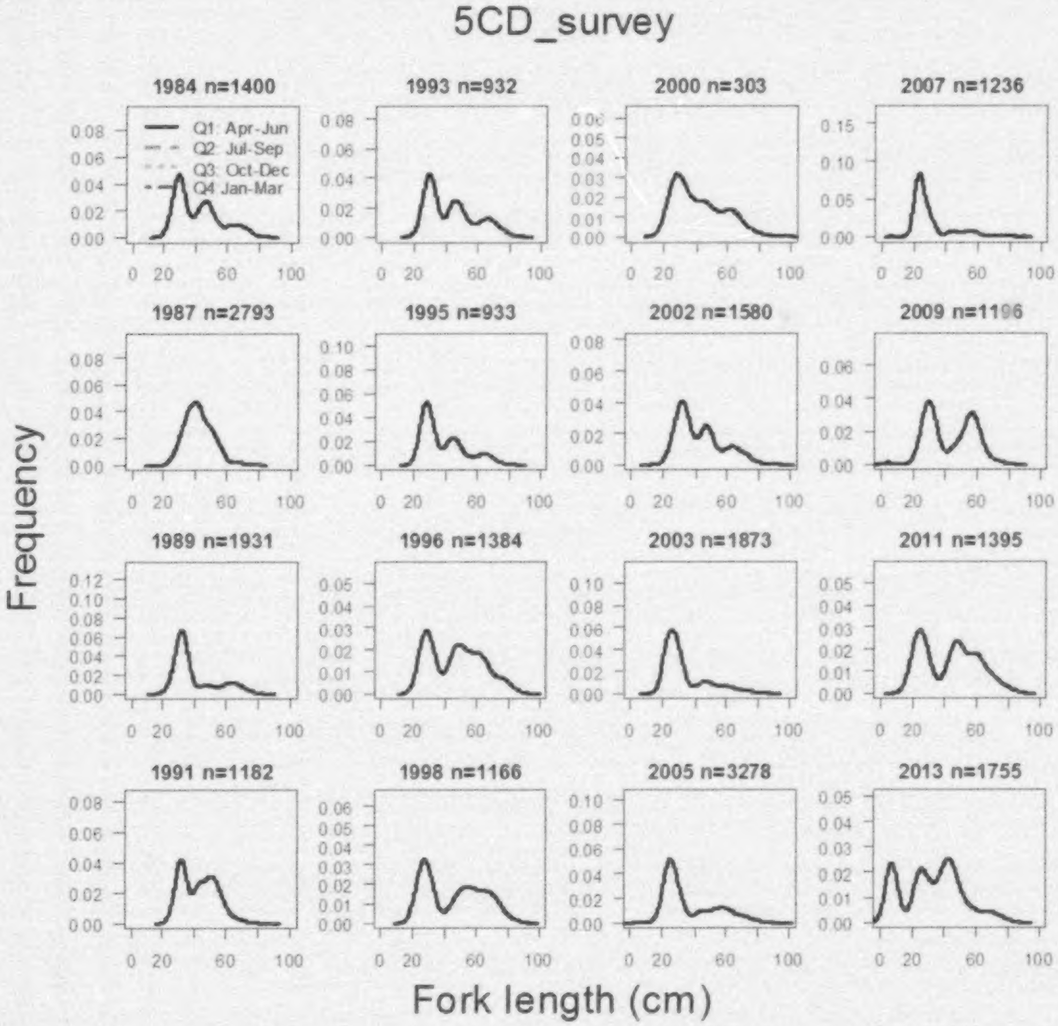


Figure D1. Length frequencies from the Hecate Strait Multispecies Assemblage surveys (1984-2003) and Hecate Strait Synoptic surveys (2005-2013).

HECATE STRAIT COMMERCIAL LENGTHS

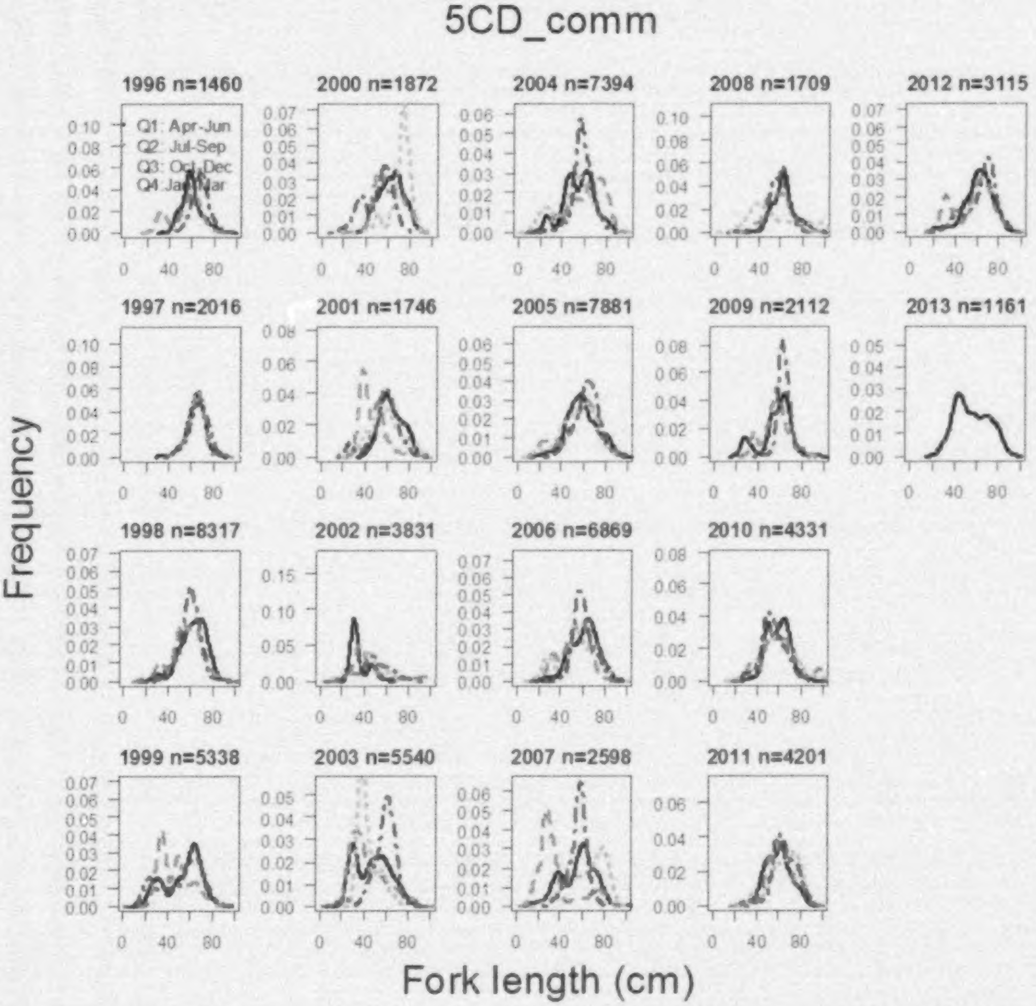


Figure D2. Length frequencies by fishing year and quarter for Pacific Cod caught in Hecate Strait by commercial trawlers, 1996-2013. Extraction based on criteria in Table 7.

QUEEN CHARLOTTE SOUND SURVEY LENGTHS

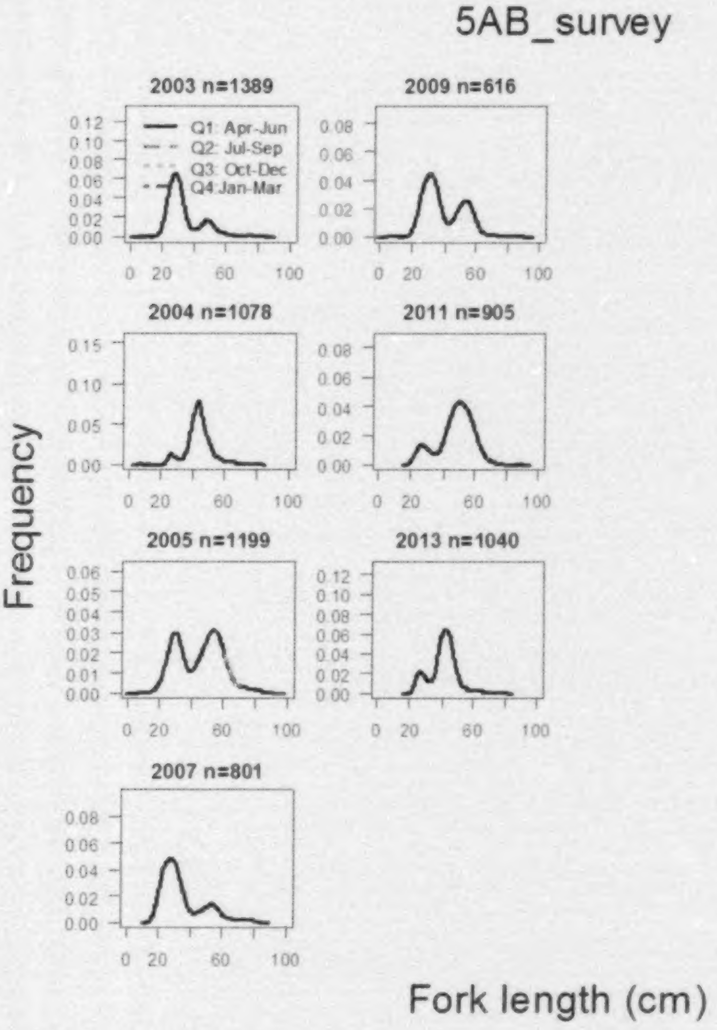


Figure D3. Length frequencies from the Queen Charlotte Sound Synoptic surveys (2003-2013).

QUEEN CHARLOTTE SOUND COMMERCIAL LENGTHS

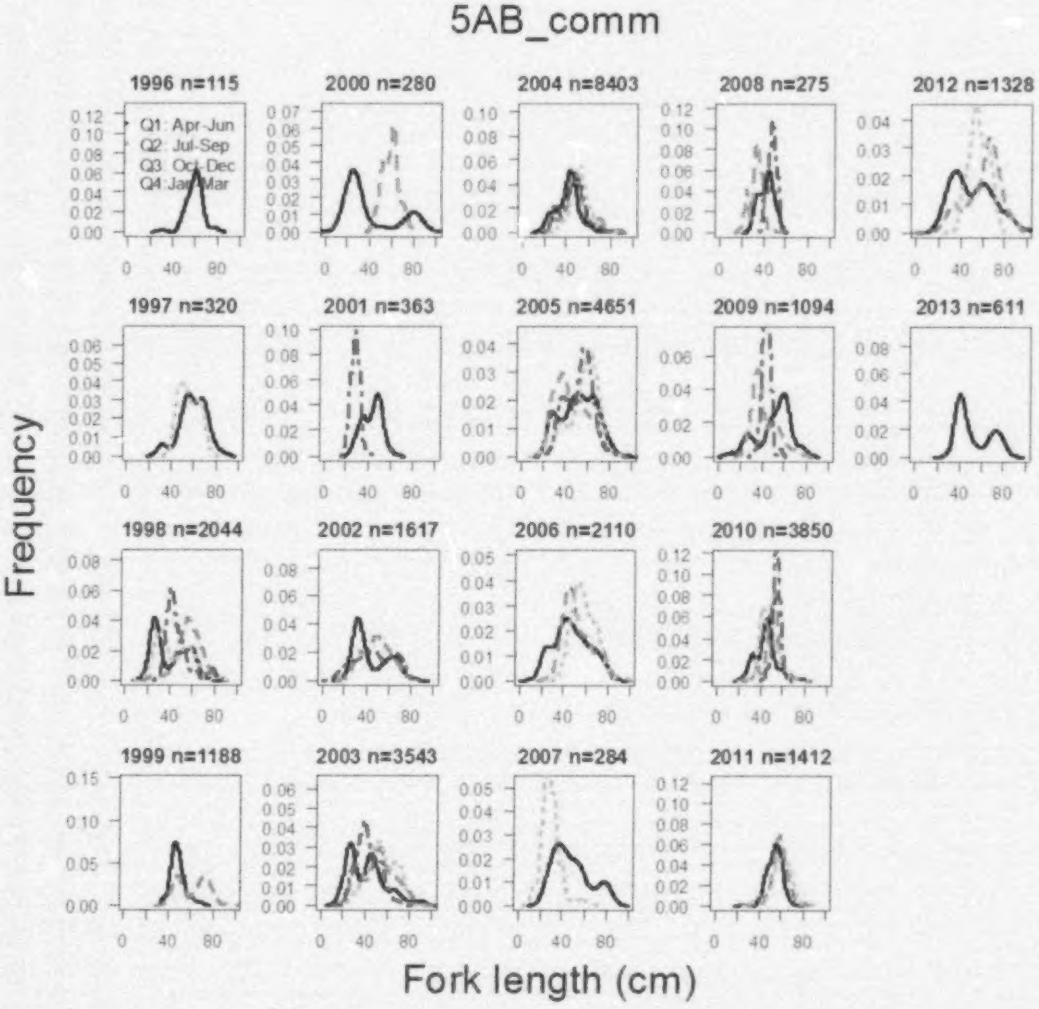


Figure D4. Length frequencies by fishing year and quarter for Pacific Cod caught in Hecate Strait by commercial trawlers, 1996-2013. Extraction based on criteria in Table 7.

APPENDIX E: GENETIC STOCK STRUCTURE OF PACIFIC COD (GADUS MACROCEPHALUS) AND RECOMMENDATIONS FOR FUTURE RESEARCH

USE OF GENETIC STOCK ID FOR MANAGEMENT

One of the main goals of fisheries genetics is to determine the boundaries of putative fish stocks that can in turn be used to determine management units (Hauser & Carvalho 2008). Genetic techniques can be used to assess the rate of gene flow or migration between regions which can in turn provide insight into the connectivity between populations and aid in determining population boundaries. Determining population boundaries is important for matching biological populations with management units (Reiss *et al.* 2009). Here we use the term stock to refer to a management unit and population to refer to a group that is defined by significant and reproducible genetic differentiation, which is largely demographically independent from other such groups (after Reiss *et al.* 2009).Understanding gene flow can also provide insight into source-sink dynamics, including the relationship between larval dispersal and adult populations (Hauser & Carvalho 2008). Maintenance of multiple populations, which may be adapted to local conditions, may be important for the long term resilience of a species and may contribute to the overall productivity of a fishery (Hilborn *et al.* 2003).

Identifying genetic structure in pelagic fish species can be challenging because such species tend to have large population census sizes with few (if any) barriers to dispersal as either juveniles or adults (Ward *et al.* 1994; Waples 1998). Thus, gene flow is often relatively unrestricted and, even if barriers to gene flow do exist, large populations tend to maintain genetic diversity which makes detecting restrictions difficult. However, an increasing number of studies have detected population structure in pelagic fishes, with evidence that this structure is biologically relevant, i.e., structure corresponds to a change in environmental parameters or to differences in a physiological trait (Atlantic Herring, Bekkevold *et al.* 2005; Atlantic Cod, Knutsen *et al.* 2011; Pacific Herring, Wildes *et al.* 2011).

Molecular markers offer a powerful tool for estimating gene flow. A variety of markers have been used in marine fishes including allozymes, mitochondrial DNA (mtDNA), microsatellites and, most recently, single nucleotide polymorphisms (SNPs). See Glossary for definitions. While all have their strengths and weaknesses, microsatellites are often favored for use over other markers due to their high degree of variability and ease of genotyping in the laboratory. In comparisons with allozymes, it has been demonstrated that microsatellites have a smaller sampling variance and greater statistical power for detecting population structure (Waples 1998; Larsson *et al.* 2007).

Several statistics can be used to assess population structure from genetic data. The most common is pairwise F_{ST}. F_{ST} is a measure of the amount of inbreeding that occurs within a group or population compared to other groups or populations (see longer description in Glossary). F_{ST} values range from 0 (complete panmixia) to 1 (total contemporary and historical isolation). Because the amount of inbreeding is affected by population size (i.e., inbreeding is greater in small populations), pelagic marine fishes, which typically have extremely large population sizes on the orders of millions of individuals, tend to have very low F_{ST} values. Ward *et al.* (1994) found that the median F_{ST} of marine fishes, calculated from a variety of species, was 0.02 and significant F_{ST} values less than 0.01 have been observed in some species (e.g., Bekkevold *et al.* 2005; White *et al.* 2010). F_{ST} is calculated based on the frequency of shared alleles between groups and significant pairwise F_{ST} values indicate whether the level of population differentiation between the groups under consideration is statistically greater than zero. Significance is typically determined by permutation testing (Welch 1990), with allele frequencies pooled and resampled in order to recalculate the test statistic (in this case F_{ST}). It must be noted that statistical significance does not necessarily mean there is an important biological difference between groups. Statistical, but not biological, significance could arise due to disproportionately sampling within a family (i.e., non-random sampling) or by detection of differences that are not large enough to be relevant to management, often by using a large number of loci (Waples 1998). The converse problem may also occur (Waples 1998; Hauser & Carvalho 2008). For example, in large marine populations, low F_{ST} values may correspond to relatively low migration rates on the order of a few 100 individuals, which may be <1% of the population. However, restricted migration, with rates of between 0.2 and 10%, has been shown to be sufficient for differential response to demographic perturbation, yet may be too low to result in significant genetic structure (Hauser & Carvalho 2008, and references therein). In addition, neutral markers reflect changes over evolutionary time and may not identify recent isolation of populations (Hauser & Carvalho 2008). Despite these caveats, F_{ST} is one of the most commonly used methods for quantifying genetic difference between groups and has been used to address questions relevant to the management of marine species (e.g., White *et al.* 2009; Selkoe *et al.* 2010; Bekkevold *et al.* 2011).

LIMITED DISPERSAL AND POPULATION STRUCTURE

The range of Pacific Cod extends along coastal shelf regions from Washington State along the northwestern coast of North America to the Bering Sea and along the north eastern coast of Asia. Pacific Cod form concentrations in defined regions and follow predictable patterns of yearly migration (Ketchen 1961; Shimada & Kimura 1994). The results of several tagging studies suggest that Pacific Cod have a limited dispersal range, although migrations of long distances have been observed (Shimada & Kimura 1994; Gustafson *et al.* 2000). Thus, connectivity between regions is likely limited, which may result in stock structuring.

RESEARCH QUESTION

Currently, Pacific Cod are managed as four stocks – West Coast Vancouver Island (WCVI), Strait of Georgia (SoG), Queen Charlotte Sound (QCS) and Hecate Strait (HS) (Sinclair & Starr 2005). Although previous genetic work has identified a difference between the fish from the Strait of Georgia and those from the Gulf of Alaska and the Bering Sea, it is unknown whether the Canadian populations are genetically distinct. And if, in particular, the Hecate Strait and Queen Charlotte Sound stocks are part of larger populations extending south from Alaska. The previous Pacific Cod assessment specifically recommended more detailed analysis of the Queen Charlotte Sound stock as there was little evidence at the time to warrant the designation of this stock as unique from other populations (Sinclair & Starr 2005). Here, we provide a review of the current state of understanding of the genetic structure of Pacific Cod and describe future research which could address the following two questions: (1) are populations from WCVI, SoG, QCS, and HS genetically distinct from each other and from US stocks, and (2) does fishing occur on mixed stocks in QCS and/or HS?

SUMMARY OF PREVIOUS GENETIC STUDIES

In the earliest assessment of genetic population structure in Pacific Cod, allozyme loci were used to assess differentiation between 11 regions located across the species range (Grant *et al.* 1987). Grant *et al.* (1987) found large differences between Asian and North American populations, a division which has been confirmed in subsequent studies (Cunningham *et al.* 2009; Canino *et al.* 2010; Kim *et al.* 2010) and is also typical for other pelagic species in the northern Pacific (Walleye Pollock, O'Reilly *et al.* 2004). This large difference between Asian and North American populations is indicative of recolonization of the Bering Sea following the last ice age when populations expanded north from glacial refugia (Canino *et al.* 2010).

In a more recent study of Pacific Cod using microsatellite markers, Cunningham *et al.* (2009) calculated an average F_{ST} of 0.005 (±0.002) and found evidence for significant isolation by distance (IBD) along the coast of North America. Thus, populations may be continuous, with no strong genetic distinction between adjacent samples; however, accumulated differences could result in samples taken from distant regions being quite different. This type of pattern represents a particular challenge for management, as distant populations may still warrant independent management, but there is no clear region in which to draw management boundaries (Cunningham *et al.* 2009). Despite the strong signature of IBD, Cunningham *et al.* (2009) also saw some modest support for barriers to gene flow between samples from the Strait of Georgia and the Washington coast, between Hecate Strait and the Strait of Georgia, and between these more southerly regions and Alaskan samples; they also detected the Asia/North American division observed in earlier studies. Canino *et al.* (2010) extended the analysis of Cunningham *et al.* (2009) with the addition of a mtDNA locus (the NADPH subunit 2 gene); findings were similar with this new marker. Due to the differentiation between Puget Sound and the Strait of Georgia, both Cunningham *et al.* (2009) and Canino *et al.* (2010) suggested that isolated populations may exist within fjords along the US and Canadian Pacific coast. Genetic differentiation between fjord and coastal populations has also been observed in Atlantic Cod (Knutsen *et al.* 2011) and Pacific Herring (Wildes *et al.* 2011).

IBD along the coast of North America was also seen by Liu *et al.* 2010 using sequence data from the control region of mtDNA. However, genetic distance was not correlated with geographic distance across all populations so environmental factors, such as currents that affect larval dispersal, may also impact isolation between regions (Liu *et al.* 2010). Indeed, there was no significant difference between samples taken from Hecate Strait and from the Strait of Georgia and the division between Southeast Alaska and the BC coast was also not observed when assessed with the mtDNA control region (Liu *et al.* 2010). Because mtDNA is clonally inherited without recombination, the allele sample size is only half that of nuclear genes (i.e., only one chromosome per individual rather than two) and all loci are linked, meaning mtDNA is treated as one locus. In addition, Pacific Cod appear to have relatively low mitochondrial sequence diversity, most likely a result of bottlenecks or founder effects following post-glacial recolonization (Liu *et al.* 2010). Thus, these genetic markers may have lower power for detecting divergence than do microsatellites with their higher mutation rate and greater variability (Waples 1998). In contrast, Canino *et al.* (2010) did find evidence of population structuring using two different mtDNA loci. The loci used by Canino *et al.* (2010) had greater nucleotide diversity than did the locus used by Liu *et al.* (2010), and thus greater statistical power for detecting between population differences, which may explain the different results of these two studies.

Strognov *et al.* (2009a; 2009b; 2010), using a different suite of microsatellite markers from those used in the study by Cunningham *et al.* (2009), found no difference between samples taken off the west coast of Vancouver Island, from the Bering Sea, or from the Sea of Okhotsk although each of these regions differed from samples taken near the Kuril Islands. However, these studies relied on only four microsatellites and it is quite likely that these markers did not have sufficient power to distinguish between populations. Furthermore, the number of fish sampled within regions varied from 50 (from the Sea of Okhotsk) to 450 (from the Bering Sea); unbalanced sampling may result in a lack of power to detect genetic differentiation (Ryman *et al.* 2006).

Two studies have also examined fine scale structure in Asian Pacific Cod populations. Kim *et al.* (2010) segregated Korean populations into two groups, southern/western and eastern populations, using microsatellites. While, Gwak and Nakayama (2011) identified three Korean populations, western, southern, and eastern, using a different suite of microsatellite markers and one mitochondrial locus.

To summarize, several studies, using a variety of molecular markers, have identified a distinction between North American and Asian Pacific Cod populations and between Alaskan populations and those south of Dixon Entrance. There is some weak evidence from the studies of Strognov *et al.* suggesting a lack of distinction across the Pacific or between Vancouver Island and Alaska. However, given the low number of molecular markers used in those studies and the more robust findings from other studies, the suggestion of no structure should be discounted. There is some evidence that samples taken off the coast of Washington and the west coast of Vancouver Island may be distinct from fish sampled within the Strait of Georgia or Puget Sound. The hypothesis has also been raised that isolated populations may exist within fjords along the coast of British Columbia. Evidence from Korean studies suggests that population differentiation can exist over relatively short distances. To date little work has been done to determine if population structure exists within BC waters. Given the findings of IBD along the coast and the suggestion that population structure can evolve over relatively short distances, additional work pertaining to population structure in BC would be of interest.

RESEARCH RECOMMENDATIONS

Sampling design

In order to address question one, genetic samples should be collected from spawning aggregations if possible. In Hecate Strait, spawning has been observed around Horseshoe Island, Reef Island and Dogfish Bank's fishing grounds, and Rose Spit and Reef Island (Sinclair & Starr 2005). Spawning sites have also been identified off the west coast of Vancouver Island and in the Strait of Georgia (Ketchen 1961). No spawning sites have been identified in Queen Charlotte Sound (Sinclair & Starr 2005) but sampling efforts from February to March may capture spawning fish if they exist in this region. Additional samples of Pacific Cod should be obtained from the Gulf of Alaska, Puget Sound and the Washington coast; these samples could be obtained from researchers at the NOAA Fisheries Alaska Center who have already collected samples for previous studies. It should be noted that the genotyping results from future work on Canadian populations cannot be compared directly with previous studies as microsatellites are notoriously difficult to standardize between laboratories; thus, samples from previously studied populations should be re-genotyped and analyzed together with newly collected samples. In order to address question two, genetic sample should be collected in QCS and HS from non-spawning populations. Both sets of samples should include adult fish rather than juveniles to minimize bias due to non-random sampling of families (Waples 1998).

Samples could consist of either fin clips or opercle punches from a minimum of 100 fish per region (WCVI, SoG, QCS and HS) both during and outside of the spawning season. Only a small amount of tissue (approximately 1 mm^3) is needed. Tissue should be stored in 95% ethanol prior to use. Because marine fishes tend to have low levels of genetic differentiation samples sizes must be larger than for anadromous or freshwater species. Samples sizes of 100 individuals per regions are recommended here as statistical modeling indicates this sample size is sufficient to identify relatively low levels of divergence and that increased sample sizes beyond 100 individuals result in low marginal returns in increased power at the F_{ST} values seen in previous studies (i.e., $F_{ST} = 0.005$) (Waples 1998).

It is also possible to obtain DNA from scale or otolith samples (Nielsen & Hansen 2008). Thus, it may be possible to use samples which have already been collected for aging or other uses provided sampling location, date and, ideally, storage conditions of any samples are known. Sample storage is important for preservation of DNA for future genetic work. Samples stored in poor conditions (i.e., high humidity, exposure to heat and/or sunlight) are more subject to DNA degradation (Nielsen & Hansen 2008). While it may be possible to extract sufficient DNA for microsatellite analysis, the quality of the DNA should be checked prior to any attempts to amplify molecular markers; this can be done by measure the optical density of extracted DNA at 260 and 280 nm or by electrophoresis (Nielsen & Hansen 2008). Contamination may also arise if samples are stored in batches. Different washing techniques may be able to eliminate potential contamination (Mitchell *et al.* 2008).

Molecular markers

Twelve markers are suggested for the assessment of population structure within the area of interest (Table 1). These markers were used in a previous study examining stock structure along the Pacific coast of North America (Cunningham *et al.* 2009). If any of these markers is uninformative in the samples in question (e.g., are found to be monomorphic, are under selection, have large allele dropout or have null alleles; please see Glossary) additional microsatellite loci have also been used with some success in Pacific Cod (Table 2) and could be tested in fish used here. The facilities exist at the Pacific Biological Station, Molecular Genetics lab, for extracting DNA and genotyping fish using microsatellites.

In general, increasing the number of independent alleles (the number of alleles at a locus minus one summed across loci), either through increased numbers of loci or use of highly polymorphic loci, increases the precision of measurements of population differentiation (Kalinowski 2002). The markers suggested here have been shown to have modest to high polymorphism in some populations of Pacific Cod.

Statistical Analysis

Microsatellite markers should be checked for adherence to Hardy-Weinberg equilibrium (HWE) values. Departures from HWE may be indicative of technical issues such as the presence of null alleles or large allele drop out (see Glossary), both of which result in a greater number of homozygotes than expected. Alternatively, departures from HWE may indicate that loci are under selection or that multiple populations are being sampled. The program MICROCHECKER can be used to calculate HWE and to distinguish between possible reasons for any deviations (van Oosterhout *et al.* 2004).

Neutrality (i.e., loci are not under selection) is a key assumption of most analyses of population structure. Therefore, microsatellites should be checked for neutrality prior to subsequent analyses. Selection can be tested with the method of Beaumont and Nichols (1996). The program LOSITAN provides a convenient graphic user interface for this method (Antao *et al.* 2008). Briefly, a neutral distribution of F_{ST} and heterozygosity values is generated using simulations of populations with the same sample size and average global F_{ST} as the actual samples. Then each marker is plotted against this neutral distribution based on pairwise F_{ST}'s and observed heterozygosity. Loci that fall outside the 95% credibility intervals of the neutral distribution are presumed to be under selection (Beaumont & Nichols 1996).

Gene diversity in populations is typically characterized by allele frequencies, heterozygosity, and allelic richness, these quantities can be calculated using either Genepop (Rousset 2009; http://genepop.curtin.edu.au/) or FSTAT (Goudet 1995; www2.unil.ch/popgen/softwares/fstat.htm). Both these programs can also be used to estimate pairwise F_{ST}; permutation tests conducted in FSTAT can determine if F_{ST} values are significant.

The F_{ST} test described above pre-supposes that populations have been correctly identified, thus making pairwise F_{ST}'s a good indicator of divergence between groups. However, it is possible that the currently defined management boundaries, upon which sampling is based, do not accurately represent genetic boundaries. The program STRUCTURE can be used to infer the number of genetic populations within a dataset (Pritchard *et al.* 2000). The program can also be used to assign individuals to previously determined populations. Thus, this program can also be used to determine of samples taken from the fishery are assigned back to the region from which samples were taken or if those individuals most likely originated from one of the other populations identified in response to question one.

IBD can be assessed in study populations by use of a Mantel test implemented in Genepop using the ISOLDE program. The Mantel test is a statistical evaluation of the correlation between two semi-matrices, in this case pairwise genetic distance (i.e., F_{ST}) and geographic distance; a significant correlation between the semi-matrices is indicative of IBD. Geographic distance between populations can be calculated from the latitude/longitude of sampling stations.

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Table E1. Recommended microsatellite markers including locus name, sequences for the forward (F) and reverse (R) primers, type of repeat motif (di, two basepair repeat; tetra, four basepair repeat; complex, mix of repeat motifs), approximate size range from previous studies, melting point (Tm) and reference paper.

Locus	**Primer seq. (5'-3')**	**Repeat Type**	**Size Range (bp)**	**Tm (°C)**	**Ref**
Gma100	F:CGGTATCGTCATTGCTGACA R:TCGCCCTTCGACTAAGTGTT	Tetra	223-393	55	Canino *et al.* (2005)
Gma101	F: ATTGTTGCTGGTGGTGTTTG R:AACCCTTTATATCTACG	Tetra	119-241	55	Canino *et al.* (2005)
Gma102	F: TGGTTTCATTCGGTTTGGAT R: GGGCTCAGGTAAAGCCTCTT	Tetra	221-275	55	Canino *et al.* (2005)
Gma103	F: TGGATGTGTGCGTCTACATTG R: AATCGCAACTGAGGTGAGTCT	Tetra	190-394	55	Canino *et al.* (2005)
Gma104	F: AAAGAGAGCCACAGCCAGAT R: ATTCAACTGTTGGCCTCTGC	Complex	168-230	55	Canino *et al.* (2005)
Gma105	F: CAAAGAGAGTGATCGCATCG R: CTGCACCCCTAGGAAGAGTG	Di	189-367	55	Canino *et al.* (2005)
Gma106	F: TCACCATCACCTAGCAACCA R: GCGGAGATGGAGGATTACTG	Tetra	179-225	55	Canino *et al.* (2005)
Gma107	F: GGGAGTGGAGTACAGGGTGA R: CCATTGTTTAACATCTGGGACA	Tetra	195-243	55	Canino *et al.* (2005)
Gma108	F: AAGTCCCAACACACCAAAGC R: CTCCTCTCTCGCGCTCTTTA	Tetra	210-280	55	Canino *et al.* (2005)
Gma109	F: CATTTTACCTTTTGCTGAGGTG R: AATTAAATTAGTTAGATGGAAAGA	Tetra	257-373	55	Canino *et al.* (2005)
Gmo37[a]	F: GGCCAATGTTTCATAACTCT R: CGTGGGATACATGGGTACT	Di	144-352	46	Miller *et al.* (2000)
Tch20[b]	F: ACATTGTAAACGGCGATTC R: TGGTTAGTCTGAGACCCAG	Complex	88-212	54	O'Reilly *et al.* (2000)

a developed for Atlantic Cod (Gadus morhua)

b developed for Walleye Pollock (Theragra chalcogramma)

Table E2. Additional microsatellite markers that have been demonstrated to amplify loci in Pacific Cod including locus name, sequences for the forward (F) and reverse (R) primers, type of repeat motif (di, two basepair repeat; tetra, four basepair repeat; complex, mix of two and four basepair repeat motifs), approximate size range from previous studies, melting point (Tm) and reference paper.

Locus	**Primer seq. (5'-3')**	**Repeat Type**	**Size Range (bp)**	**Tm (°C)**	**Ref**
KGM9	F: GCAGTGTGTATCGGTGTGT R: CATGTGTTCTGATTCGAGTTA	Di	300-370	54	Kim *et al.* (2010)
KGM12	F: TCCTTCAACAACTTGCTCTAT R: AGAAGCTAGGCCATAACATTA	Di	174-192	54	Kim *et al.* (2010)
KGM26	F: TCCTTCAACAACTTGCTCTAT R: GAACTGAATAAATGCCAGGTA	Di	190-224	52	Kim *et al.* (2010)
Gmo19[a]	F: CACAGTGAAGTGAACCCACTG R: GTCTTGCCTGTAAGTCAGCTTG	Tetra	120-220	50	Miller *et al.* (2000)
Gmo34[a]	F: TCCACAGAAGGTCTCCTAA R: GGTTGGACCTCATGGTGAA	Tetra	80-120	50	Miller *et al.* (2000)
Tch5[b]	F:GCCTTAATATCACGCACA R:TCGCATTGAGCCTAGTTT	Tetra	186-280	42	O'Reilly *et al.* (2000)
Tch8[b]	F: CGCTAATCAAATAACATGC R:ATCGTACCTCCAGTTAAATAG	Tetra	125-229	42	O'Reilly *et al.* (2000)
Tch9[b]	F: TATCCATCCATCCAAATATC R: AGATACATCCATAGCAAGGAA	Tetra	98-146	49	O'Reilly *et al.* (2000)
Tch17[b]	F: GTCTGTCTGCCCGTGAGT R: AGCCAGTGGCATTTGTTC	Tetra	165-245	54	O'Reilly *et al.* (2000)
Tch19[b]	F: TATGCTGATTGGTTAGGC R: GATCATTTGTTTCAGAGAGC	Tetra	74-158	51	O'Reilly *et al.* (2000)

[a] developed for Atlantic Cod (*Gadus morhua*); the size ranges and Tm given here are were identified in Atlantic Cod and may vary in Pacific Cod

[b] developed for Walleye Pollock (*Theragra chalcogramma*); the size ranges and Tm given here were identified in Walleye Pollock and may vary in Pacific Cod

GLOSSARY OF GENETIC TERMS

Allozymes: A variant of an amino acid within an enzyme which arises due to different alleles at a single locus; variants are detected by changes in electrophoretic mobility of the protein through a gel. Typically variants do not result in a change in function of the protein and thus are considered evolutionarily neutral.

Effective population size, N_e: The number of individuals in a randomly mating population, with all individuals having equal reproductive success that would have the same level of genetic variation and inbreeding as that seen in the study population. The effective population size is typically smaller (and often much smaller) than the census population size.

F_{ST} : F_{ST} (aka the fixation index) is a measure the reduction in heterozygosity due to inbreeding within a subpopulation. F_{ST} can also be thought of as the proportion of genetic variation contained within a subpopulation (S) compared to the total genetic variation (T) combined across all subpopulations. The statistic can be calculated based either on whether randomly drawn alleles are identical by descent (i.e., the same allele due to inheritance from a common ancestor) or identical in state (i.e., the same allele as a function of how frequently that allele occurs in the population). Because it is rare to know if an allele is identical by descent (a detailed pedigree is necessary), F_{ST} is typically estimated based on identity in state and a variety of methods have been devised to this effect. The most common method used for estimating F_{ST} is that of Weir and Cockerham (1984)

$$F_{ST} = \frac{Q_2 - Q_3}{1 - Q_3}$$

where Q_2 is the frequency of identical pairs of genes (i.e., the same allele at a locus) between individuals within subpopulations and Q_3 is the frequency of identical pairs of genes between subpopulations. Values for F_{ST} range from 0 (panmixia) to 1 (complete isolation).

Isolation by distance, IBD: Populations which are geographically farther apart tend to be more genetically distinct because they are less likely to exchange migrants. IBD is often found along an environmental gradient, within river systems or along coastlines.

Large (or upper) allele dropout: Sometimes large alleles fail to be amplified in a PCR reaction. This often occurs because of the preferential amplification of smaller alleles due to competition for primers and nucleotides within the PCR reaction (Wattier *et al.* 1998). Once even a small imbalance occurs, the amplification process will result in the final PCR product containing an exponentially greater number of shorter alleles. Upper allele dropout has been observed to occur more frequently when there is a large size difference between alleles in a heterozygous individual (Wattier *et al.* 1998). Upper allele dropout results in an excess of homozygous individuals, particularly of individuals homozygous for smaller alleles. The problem can sometimes be corrected by using a greater starting amount of DNA or by varying PCR conditions (i.e., increasing the extension time). Occasionally, the problem is simply due to searching within an incorrect size range for alleles during analysis in which case the problem can easily be corrected by increasing the size range.

Locus: a specific location in the genome. A variant at a locus is an **allele**.

Microsatellites: A segment of non-coding DNA which consists of short, repeated segments (typically 2, 3 or 4 basepair repeats). The number of repeated segments may vary considerably between individuals. These markers are inherited in a Mendelian fashion. Microsatellites are considered evolutionarily neutral because they are non-coding although in some cases they may be so closely associated with a functional gene under selection that they appear to be under selection. The assumption of neutrality can be tested using the program LOSITAN (Antao *et al.* 2008) which assesses the level of genetic differentiation between populations (F_{ST}) compared to the heterozygosity of a locus

Molecular markers: Any fragment of DNA which can be reliably identified or located within the genome.

Null allele: An allele at a locus that contains a mutation in the priming site so that the allele is not amplified during PCR. Null alleles are often assumed to be present if a population has an unexpectedly high number of individuals that are homozygous at that locus.

Polymerase Chain Reaction, PCR: PCR is a biochemical technique to quickly and reliable generate millions of copies of a segment of DNA. With new refinements of the technique it is possible to generate new copies from as little as one copy of starting material. The method relies on thermalcycling and the heat stable enzyme *Taq* polymerase to assemble DNA strands in a manner similar to that of a cell. The PCR reaction mixture contains the purified DNA template; the nucleotides adenine, cytosine, guanine and thymine (collectively, dNTPs); *Taq* polymerase; a buffer solution and other stabilizers (typically $MgCl_2$); and sense and antisense primers, which can either be specific to a targeted segment or generic depending on the application. DNA strands are heated to 96°C until they denature (i.e., the hydrogen bonds between basepairs are broken and the DNA becomes single stranded). The temperature is lowered until the primers anneal to the single stranded DNA; the annealing temperature is usually, but not always, about 3°C below the melting point (T_m) of the primers. The temperature is then raised to 72°C, the optimum temperature for the polymerase, and the new DNA strand is synthesized by adding dNTPs along the template strand starting from the end of the primer. The cycle is repeated with the newly synthesized strands serving as a template in the next round; thus, resulting in an exponential increase in copies of target DNA. PCR is most efficient when the primers match the target DNA exactly, but by manipulation of annealing temperature and reaction mix, it is possible to have some mismatches in the priming site. This means that primers developed for one species can often be used to amplify loci in another, closely related species that may have only a few differences in the priming site for the locus in question.